

Report No. 584

STRENGTH OF WELDED AIRCRAFT JOINTS

By W. C. BRUEGGEMAN

SUMMARY

The work described in N. A. C. A. Technical Report No. 348 showed that the insertion of gusset plates was the most satisfactory way of strengthening a joint. The additional tests of the present series show that joints of this type could be improved by cutting out the portion of the plate between the intersecting tubes.

T and lattice joints in thin-walled tubing $1\frac{1}{2}$ by 0.020 inch have somewhat lower strengths than joints in tubing of greater wall thickness because of failure by local buckling. In welding the thin-walled tubing, the recently developed "carburizing flux" process was found to be the only method capable of producing joints free from cracks. The "magnetic powder" inspection was used to detect cracks in the joints and flaws in the tubing.

The strengths of chromium-molybdenum T, lattice, and butt joints were materially increased by heat treatment. Butt joints in chromium-molybdenum sheet and tubing welded with low-carbon and chromium-molybdenum welding rod and those welded by the "carburizing flux" process had about the same strength in the "as welded" condition. The chromium-molybdenum and carburizing flux welds were the strongest after heat treatment.

INTRODUCTION

This investigation is a continuation of work started in 1928 at the request of and with the financial assistance of the National Advisory Committee for Aeronautics, and published by the Committee as Technical Report No. 348: Strength of Welded Joints in Tubular Members for Aircraft. It covers additional tests on joints reinforced by inserted gusset plates, tests of joints made with low-carbon and chromium-molybdenum welding rods, and the recently developed "carburizing flux" welds, and new tests made on T joints in which the leg of the T was loaded as a cantilever beam. Tests were also made on joints in thin-walled chromium-molybdenum tubing. Joints were tested in both the heat-treated and "as welded" conditions.

MATERIAL

Steel tubing and sheet of the following materials and sizes were used:

Chromium-molybdenum steel

Tubing—1 inch O. D. (O. D.=outside diameter) by 0.035-inch wall.

$1\frac{1}{2}$ inches O. D. by 0.020-inch wall.

$1\frac{1}{2}$ inches O. D. by 0.058-inch wall.

$1\frac{1}{2}$ inches O. D. by 0.083-inch wall.

Sheet—thickness 0.031, 0.063, 0.125, and 0.188 inch.

Mild-carbon steel

Tubing— $1\frac{1}{2}$ by 0.058 inch.

Sheet—thickness 0.063 inch.

The tubing and sheet complied with the following Navy Department specifications:

Chromium-molybdenum steel

Tubing—44T18¹

Sheet—47S14a

Mild-carbon steel

Tubing—49T1

Sheet—47S17a

The tensile strengths of the tubes from which the T joints were made are given in table I. Each value is the average strength of two specimens cut from opposite ends of the tube from which the members of the joints were taken. When the joint was heat-treated the tensile specimens were given the same heat treatment. Results of chemical analysis of the materials are given in table II.

TABLE I.—TENSILE STRENGTHS OF MEMBERS OF T JOINTS

| Joint No. | Figure | Tensile strength | |
|-----------|--------|------------------|-------------|
| | | A | B |
| | | lb./sq. in. | lb./sq. in. |
| G140 | 10 | 107,500 | 107,500 |
| G260 | 10 | 109,600 | 109,600 |
| H140 | 10 | 148,100 | 155,500 |
| H260 | 10 | 152,500 | 155,500 |
| K140 | 10 | 85,900 | 85,900 |
| K260 | 10 | 83,300 | 83,300 |
| L140 | 11 | 134,900 | 134,900 |
| L260 | 11 | 130,100 | 130,100 |
| J140 | 11 | 129,400 | 129,400 |
| J260 | 11 | 125,800 | 125,800 |
| GM140 | 14 | 107,400 | 102,600 |
| GM260 | 14 | 102,800 | 102,600 |
| GM440 | 14 | 107,400 | 102,600 |
| HM140 | 14 | 149,100 | 161,400 |
| HM260 | 14 | 149,100 | 152,900 |
| KM140 | 15 | 81,300 | 81,300 |
| KM260 | 15 | 85,200 | 85,200 |

¹ This specification has been superseded by Navy Department specification 44T18a and supplement 44T18b. The tubing also complied with the new specification.

TABLE II.—CHEMICAL COMPOSITION OF TUBING, SHEET, AND WELDING ROD

| Material | Carbon percent | Manganese percent | Phosphorus percent | Sulphur percent | Silicon percent | Chromium percent | Molybdenum percent |
|---|----------------|-------------------|--------------------|-----------------|-----------------|------------------|--------------------|
| Tubing: | | | | | | | |
| Chromium-molybdenum steel: | | | | | | | |
| 1 inch O. D. by 0.035-inch wall | 0.27 | 0.43 | 0.01 | 0.012 | | 0.89 | 0.20 |
| 1½ inch O. D. by 0.020-inch wall | .27 | .57 | .01 | .012 | | .94 | .20 |
| 1½ inch O. D. by 0.058-inch wall | .34 | .54 | .023 | .011 | | 1.09 | .19 |
| 1½ inch O. D. by 0.058-inch wall | .34 | .50 | .023 | .010 | | 1.08 | .19 |
| Mild-carbon steel: | | | | | | | |
| 1½ inch O. D. by 0.058-inch wall | .28 | .52 | .019 | .019 | | | |
| 1½ inch O. D. by 0.058-inch wall | .24 | .52 | .020 | .016 | | | |
| Sheet: | | | | | | | |
| Chromium-molybdenum steel: | | | | | | | |
| 0.031-inch thickness | .30 | .42 | .015 | .008 | | .89 | .18 |
| 0.063-inch thickness | .32 | .41 | .016 | .004 | | .90 | .20 |
| Welding rod:¹ | | | | | | | |
| ¼-inch diameter, carburizing flux type | .17 | 1.02 | .02 | .024 | 0.38 | | |
| ¼-inch diameter, chromium-molybdenum type | .41 | .90 | .02 | .006 | .58 | 1.13 | .20 |

¹ The low-carbon steel welding rod was from the same lot used in the previous investigation. The chemical composition is given in N. A. C. A. Technical Report No. 348, table VII.

PREPARATION OF SPECIMENS

INSPECTION FOR DEFECTS

Method.—Visual inspection of specimens of the previous investigation showed that there were cracks in some of the joints. It was found by experience that it was impossible to detect all of the cracks by visual inspection. Inasmuch as cracks may weaken the joint to an indeterminate extent, it was considered desirable to use a more effective method of inspection.

In 1922 William E. Hoke patented ² a "method of and means for detecting defects in paramagnetic material" by magnetizing the object "while in proximity to mobile, finely divided paramagnetic material" such as iron filings or powder. A crack lying across the magnetic path presents a relatively high magnetic reluctance. An appreciable difference in magnetic potential thus exists between the two sides of the crack, and if close to the surface there is an external leakage flux between them. When the iron filings are brought into the field of this leakage flux they are attracted to the edges of the crack which is then indicated by an accumulation of the filings. The test may be carried out by immersing the object to be inspected in a fluid bath in which the iron filings are suspended.

In 1927, Roux (reference 1)³ described a method of testing butt welds in steel plates by producing a magnetic flux in the plate and obtaining a pattern of the leakage flux by sifting iron filings onto a paper placed on the weld. A defective weld having no penetration, for example, has a higher magnetic reluctance than a corresponding portion of the base metal. This is indicated by magnetic leakage from the metal into the air around the defect, causing an accumulation of the powder at the defect. The joint was magnetized by a portable electromagnet with pole pieces which span the weld. By properly interpreting the pattern assumed by the iron filings the operator can often detect the presence of defects.

This method has been used in the United States by Watts (reference 2).

Recently de Forest (reference 3)⁴ has developed a technique for inspecting steel and iron for such defects as cracks and other discontinuities. His technique is similar in principle to that of Roux and Watts and consists in suitably magnetizing the object, then sprinkling the magnetic powder onto the surface.

The magnetic powder method appeared to offer a solution to the problem of locating these cracks, and arrangements were therefore made with Professor de Forest to cooperate in the inspection of the joints used in this investigation.

Seams.—Each piece of tubing and sheet was inspected for defects before welding. The apparatus for detection of seams in tubing is shown in figure 1. The tube A was slipped over the copper rod B which was connected to the transformer C. An electric current in the rod produced a circumferential magnetization in the tube. Circumferential magnetization was used because it was believed that any defects originating during the processes of manufacture would probably be longitudinal. A current of from 200 to 300 amperes was found to be satisfactory. D is an ammeter and E is a current transformer for measuring the current. The dust was applied from the shaker F.

Many longitudinal seams were found. Typical indications are shown in figures 2 and 3. The seams were usually less than 1 inch long although some were 4 or 5 inches in length. The seams generally occurred singly, but sometimes in groups of two or more as in figure 2.

² U. S. Patent No. 1426384, Aug. 22, 1922.

³ A more complete description of the technique of testing welds by the magnetographic method is given in a paper "Magnetic Testing of Welds", published in the *Welding Engineer*, vol. 15, no. 2, February 1930, p. 31. This paper was translated from material obtained from the laboratory of La Soudure Autogène Française.

⁴ See also U. S. Patent No. 1960898, May 29, 1934.

Where defects were indicated, several of the tubes were sectioned as indicated by the dotted lines in figures 2 and 3, and examined under the microscope. The seams were in approximately a radial direction and varied in depth from about 0.003 to 0.015 inch. They were partially filled with iron oxide. The etched cross section at A, figure 2, shows the surface of the tube and the seam to be decarburized. It is probable that the

Some of the tubes had grooves on the inside surface as shown at B and C, figure 3. These grooves were visible without using the magnetic powder and apparently were formed when the tube was drawn over a mandrel. When the powder was applied, as in the inspection for seams, the grooves were indicated by longitudinal accumulations of powder extending the full length of the tube as in tubes 5 and 6, figure 3.

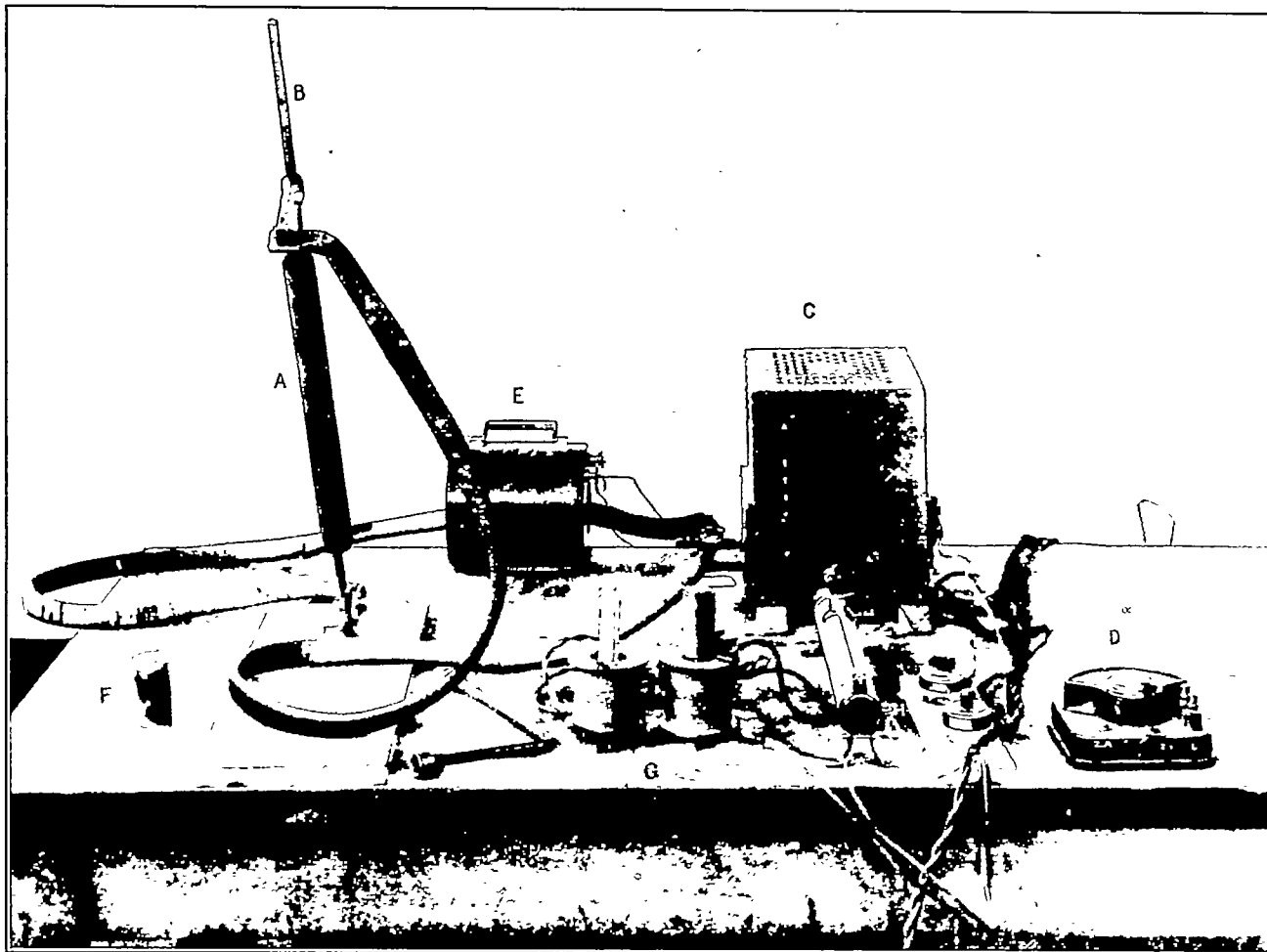


FIGURE 1.—Apparatus for detecting seams in tubing by the magnetic powder method of inspection. The tube A was magnetized by a heavy alternating current produced in the copper rod B by the transformer C. The ammeter D was used with the current transformer E to measure the current. The magnetic powder was applied to the surface of the tube by means of the shaker F. The iron-cored coils G were used when a portable magnetizing apparatus was desired.

seams originated during the fabrication of the steel and were caused by surface imperfections being rolled or drawn into the material.

There were seams on the inside as well as the outside of the tubes. It is difficult to inspect the inside surfaces, particularly of long tubes of small diameter. However, deep seams which occurred on the inside could usually be detected by applying the dust on the outside. It is believed that very few of the seams could have been detected visually without the magnetic powder.

Seams were found in the carbon-steel tubing and in two sizes ($1\frac{1}{2}$ by 0.058 inch and 1 by 0.035 inch) of chromium-molybdenum steel tubing.

The tubes were not rejected because of the presence of seams and grooves. The joints did not rupture at these defects and there was no indication that the strength was lowered under static loading.

The effect of seams and grooves on the torsional and fatigue properties of the tubing was not investigated.

Cracks.—All welded joints were examined for cracks by means of the magnetic powder method. The heat-treated joints were inspected again after heat treatment. The technique was similar to that employed for detecting seams.

The electromagnet shown in figure 4 was used to magnetize the joints. It consists of a solenoid having about

500 turns of No. 18 magnet wire and two steel pole pieces connected by a steel bar. When inspecting joints in tubular members V blocks were used on the ends of the pole pieces. These could be rotated about the axes of the pole pieces. The joint was placed in contact with the V blocks in such a manner that the flux passed

magnetic circuit is not so efficient as one in which the core is continuous, as in figure 4. A current of about 1 ampere was found to be satisfactory for both kinds of apparatus.

When inspecting the sheet samples the electromagnet (fig. 4) was used, replacing the V blocks on the pole

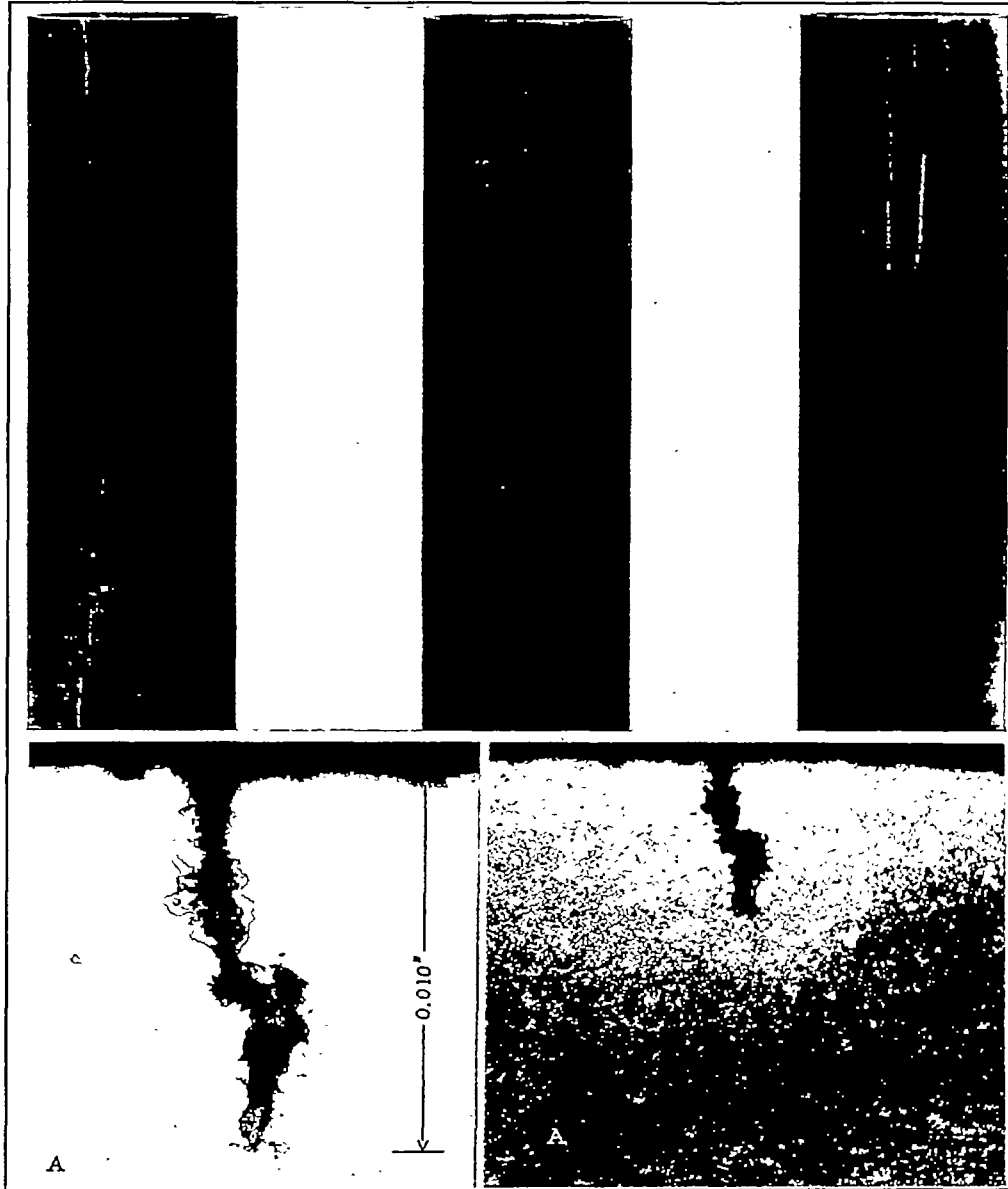


FIGURE 2.—Seams in chromium-molybdenum tubes $1\frac{1}{2}$ inches O. D. by 0.058-inch wall. A microscopic examination was made at the cross section shown by the dotted line. The seam at point A is shown in the photomicrographs (left) in the unetched cross section and at a lower magnification (right) after the cross section had been etched in 1-percent Nital.

through the portion of the joint it was desired to examine. It was sometimes more convenient to use a portable magnetizing apparatus, in which case the two coils F (fig. 1) were used. These are of the same size as the coil shown in figure 4 and are connected in series. Each coil has a laminated iron core about 6 inches long which is placed in contact with the members of the joint. It was necessary to use the coils close together because the

pieces with flat blocks. No cracks, seams, or other defects were found in the sheets either before or after welding.

Cracks were found in all joints made in thin-walled chromium-molybdenum tubing $1\frac{1}{2}$ by 0.020 inch in which low-carbon welds were made. Figures 5, 6, and 7 show locations of cracks as outlined by the magnetic powder. In the photomicrographs taken at point A,

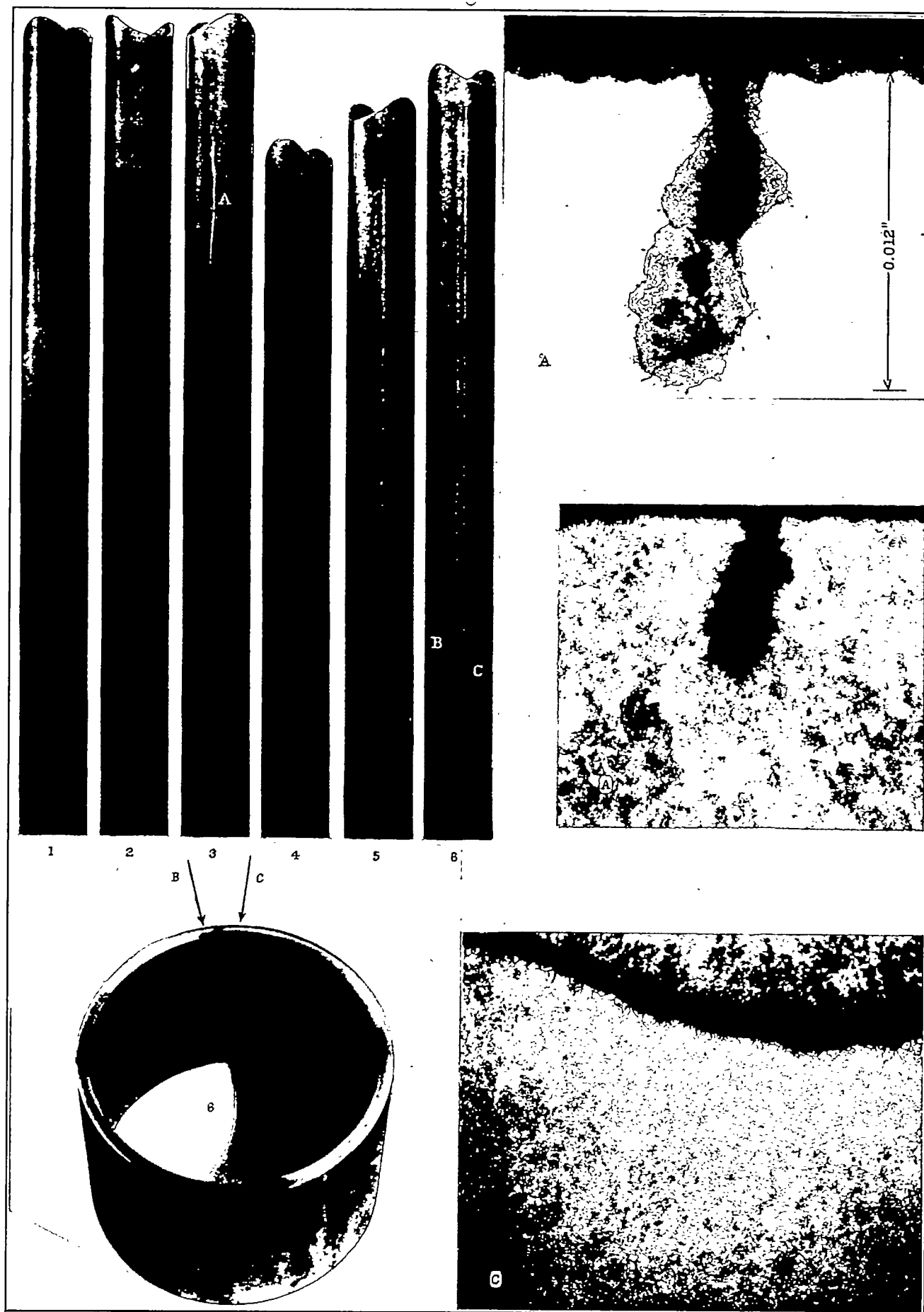


FIGURE 3.—Seams and grooves in other chromium-molybdenum tubes $1\frac{1}{2}$ inches O. D. by 0.058-inch wall. The seam at point A, tube 3, is similar to the one shown in figure 2. The powder accumulations on tubes 5 and 6 are caused by grooves inside the tube as shown in the end view of tube 6. The photomicrograph C shows the cross section adjacent to groove C.

figure 5, there are cracks apparently following the grain boundaries that existed when the steel was in the austenitic state. There were cracks on both the inner and outer surfaces of the tube and one goes com-



FIGURE 4.—Examining a lattice joint for cracks by the magnetic powder inspection.

pletely through the wall. These cracks are partly filled with oxide.

The majority of the cracks were less than one-half inch long although in the T joints shown in figure 7 they extend on one side nearly half the circumference of the tube. The cracks occurred in the base metal of joints in thin-walled tubing made with low-carbon welds, usually about one thirty-second inch from the toe of the fillet, and ran parallel to the fillet.

WELDING

The specimens were welded in the same manner as those of the previous investigation by Mr. J. C. Kushner, of the Keystone Aircraft Corporation. The welding supervisor was H. S. George, research engineer of the Union Carbide and Carbon Research Laboratory. The procedure specifications were prepared for the previous investigation by a Committee on Welding Procedure of the American Bureau of Welding, and are given in N. A. C. A. Technical Report No. 348. The welder complied with the qualification tests of the procedure specifications.

The welding supervisor witnessed all of the welding. In his opinion the joints welded with low-carbon rod complied with the procedure specifications (the specifi-

cations had been prepared to apply only to this type of weld).

Four sets of welding equipment were loaned by manufacturers. They are designated as A, B, C, and D, as shown in figure 8. The set used for each joint is indicated at the bottom of the figure showing the test results.

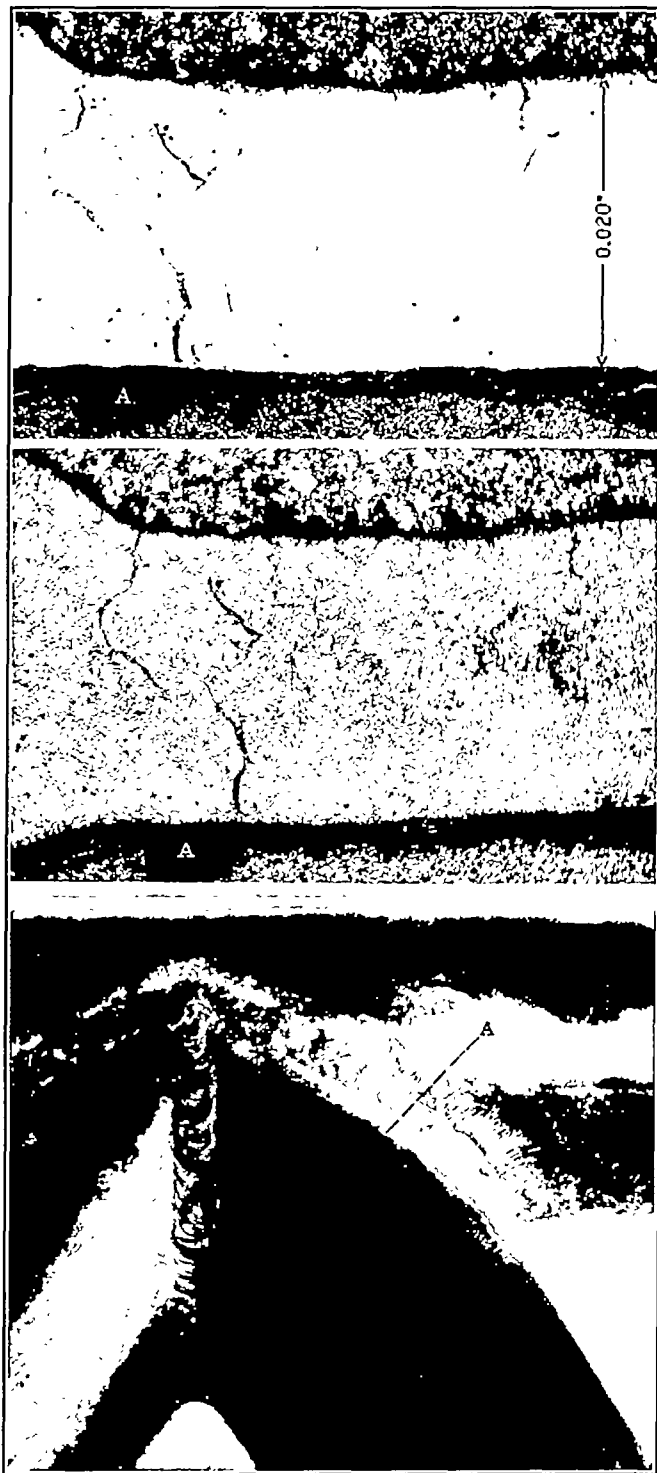


FIGURE 5.—Typical magnetic powder indications of cracks formed during welding in a lattice joint made from thin-walled chromium-molybdenum tubing ($1\frac{1}{2}$ inches O. D. by 0.020-inch wall). The photomicrographs taken at point A show the cross section indicated by the dotted line (upper) unetched and (middle) etched in 1-percent Nital. Low-carbon welding rod and a neutral flame were used in welding this joint.

All tubular joints were welded in a suitable jig that held the members in alinement. The time required to complete the weld after the members were set up in the jig was recorded.

It was found impossible to avoid cracks in thin-walled tubing when welding with a low-carbon rod. Several expedients that were tried in attempting to avoid cracks were: Preheating the tubes at the joint before welding by heating to a red heat with the torch; removing all scale adjacent to the weld with emery cloth; minimizing contraction stresses by heating one side of the joint with a torch while welding the other side; using various sizes of beads; exercising care to prevent excessive penetration; trying both forward and backward welding; using small sizes of torch tips and



FIGURE 6.—Cracks in butt joints made with thin-walled tubing ($1\frac{1}{2}$ inches O. D. by 0.020-inch wall) as indicated in the magnetic powder inspection. These joints were welded with low-carbon rod and a neutral flame.

of welding rod; and, where the end of a tube was welded to the wall of another continuous tube, sawing out the portion of the continuous tube which is covered by the end of the intersecting tube. None of these expedients was successful.

After unsuccessful attempts to weld the thin-walled tubing the welding supervisor suggested that a new welding process recently invented by him might prove successful. This process (reference 4)⁵ utilizes the carburized film caused by the absorption of carbon by steel when the latter is heated to a temperature somewhat below its melting point, in a carburizing atmosphere.

The usual type of oxyacetylene torch may be used; the gas flow is adjusted, however, to have an excess of acetylene, producing a carburizing atmosphere. The surface of the base metal when heated to the proper temperature absorbs carbon from this atmosphere. In-

creasing the carbon content of steel lowers the temperature at which it may be fused; thus a thin liquid film of melted steel is formed on the surface of the base metal at a temperature several hundred degrees lower than the fusion temperature of the base metal itself. The film, which may be recognized by its characteristic wet appearance under the flame, forms ahead of the

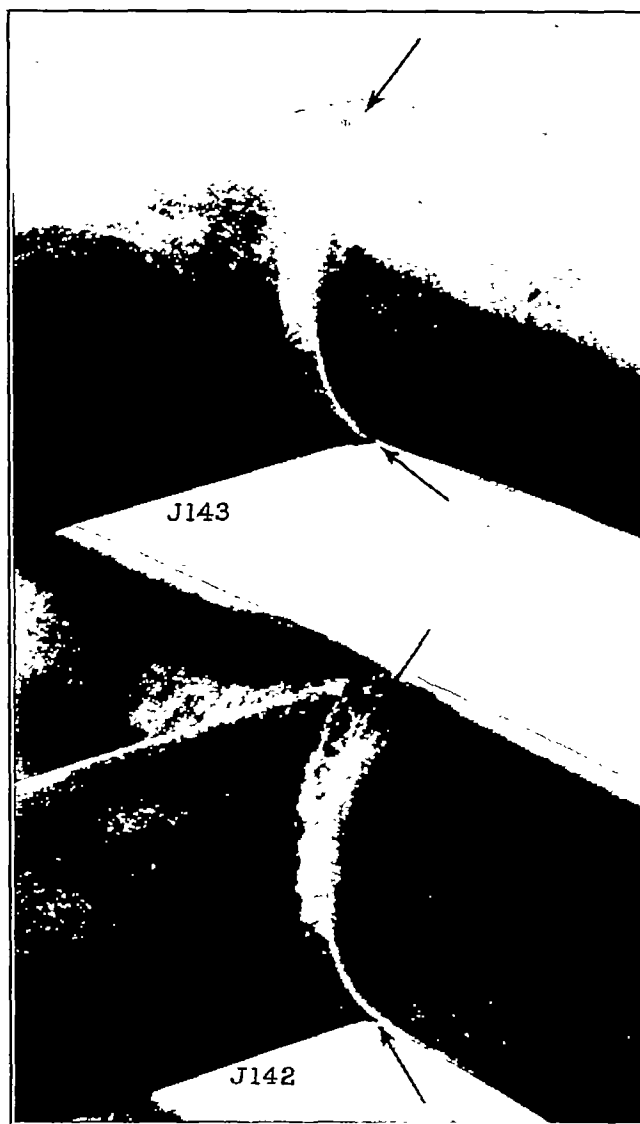


FIGURE 7.—Cracks in T joints made with thin-walled tubing ($1\frac{1}{2}$ in. O. D. by 0.020 in. wall) as indicated in the magnetic powder inspection. Low-carbon welding rod and a neutral flame were used in welding these two joints.

advancing melted filler metal and acts as a flux by preventing oxidation and causing intimate union between the base and the filler metals. The fluxing action of this film makes it unnecessary to heat the base metal to its melting point. The technique is somewhat like brazing in this respect, although all of the characteristics of a true weld are attained. A special rod containing carbon, manganese, and silicon as alloying elements in the iron base is used.

⁵ See also U. S. Patent No. 1073341, Sept. 11, 1934.

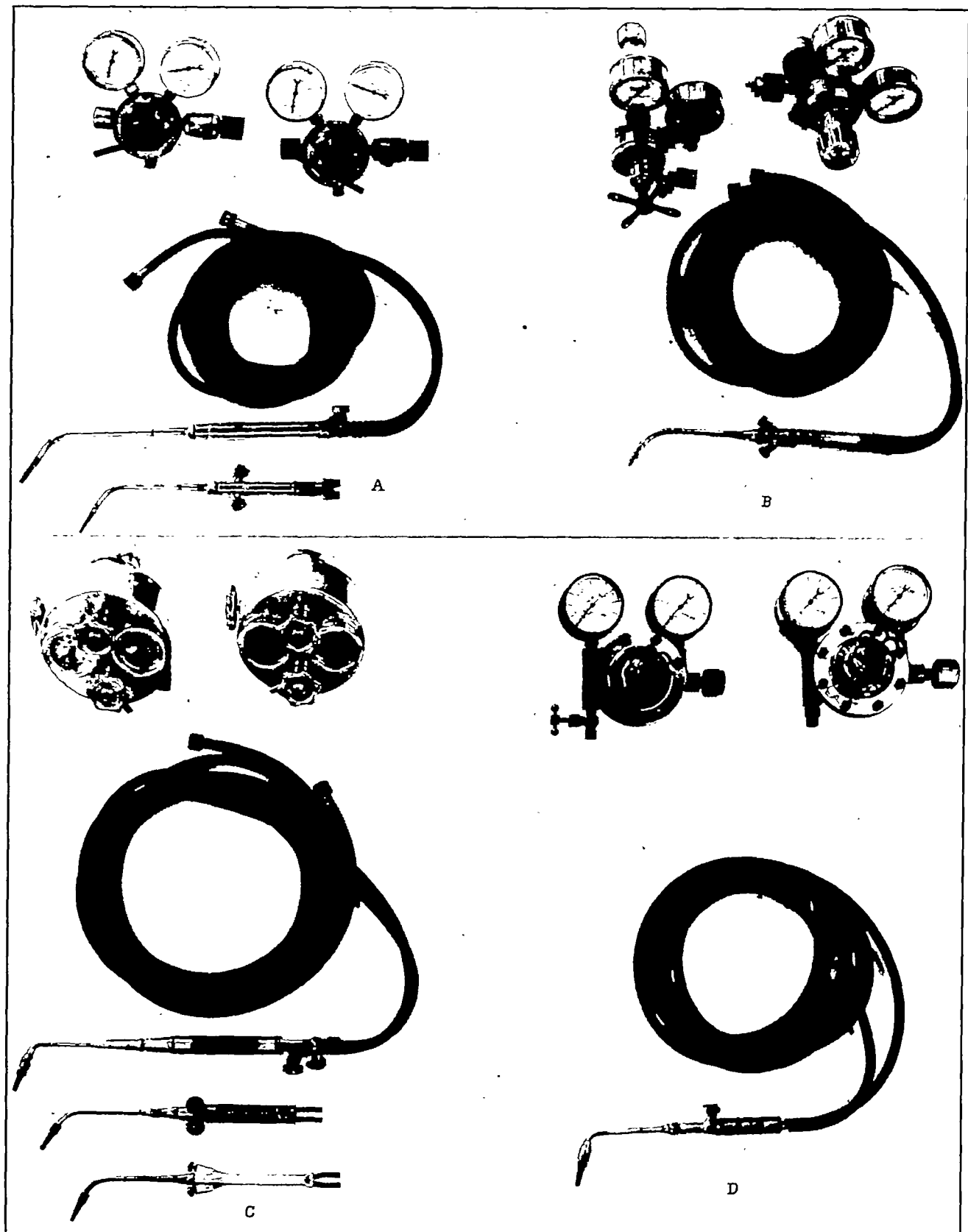


FIGURE 8.—The torches and equipment used. Each set was used to weld about an equal number of specimens.

It was believed that welds made in the thin-walled tubing by this process would be less susceptible to cracking because it would be unnecessary to fuse the base metal. Some preliminary welds were made by the carburizing flux process, and after several days' practice the welder, who had little previous experience with this process, was able to make welds in the thin-walled tubing in which no cracks could be detected.

A series of T, lattice, and butt joints was made in this tubing by the carburizing flux process, using a rod having the chemical composition given in table II. No indications of cracks could be detected by means of the magnetic powder inspection.

A brief description of some special features that were employed in making carburizing flux welds in thin-walled tubing is as follows:

(1) The luminous feather in the welding flame, indicating the amount of acetylene in excess of that required for complete combustion, was maintained at a length of from 2 to $2\frac{1}{2}$ times the length of the inner cone.

(2) Backward welding (see fig. L, N. A. C. A. Technical Report No. 348) was used; that is, the torch was held so that the flame issued in the opposite direction to that of the progressing bead. This was done to retard the rate of cooling of the fillet during the critical interval when the base metal was most susceptible to the formation of heat cracks. It is believed that less oxidation of the unwelded base metal occurs in backward welding and that the base metal is less likely to be overheated. "Forward" welding was used for all tubes having a wall thickness of 0.035 inch or more welded by the carburizing flux process and for all low-carbon welds made by the regular neutral flame technique.

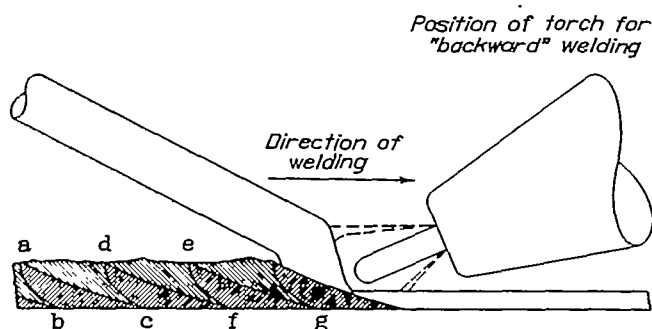


FIGURE 9.—Diagram of bead used in making carburizing flux welds in thin-walled tubing showing how the puddle was made to solidify in increments.

(3) An additional precaution consisted of manipulating the torch so as to confine the melted puddle to as small an area as possible. Instead of maintaining a continuously melted puddle as would be done on heavier base metal the fillet was made to solidify in increments. Starting with a puddle (fig. 9) having a long slope from the top of the fillet a to the point of farthest advance c, the torch was withdrawn until the

first puddle had begun to solidify on the bottom (still maintaining the carburizing atmosphere), then more reinforcement a c d was added. After this layer had begun to solidify along the line c d, the next layer d c f was added and so on. The carburized film that was formed on the surface of the overlapping layers as well as on the base metal insured a continuous bead, the layers being welded to each other in the same manner as they were welded to the base metal. Thus the minimum amount of heat was applied to the joint and the length of the puddle, measured in the direction of welding, was kept as short as possible, minimizing the amount of the contraction as the puddles cooled.

Chromium-molybdenum welding rods having the chemical composition given in table II were used to make some of the butt joints that were to be heat-treated after welding.

Henceforth joints welded with low-carbon rod, chromium-molybdenum rod and those welded by the carburizing flux process are termed low-carbon welds, chromium-molybdenum welds, and carburizing flux welds, respectively.

The butt joints in steel sheets were made with reinforcements on each side about equal to half the sheet thickness, making the total thickness of the weld about twice that of the sheet. This type of weld was used to provide a symmetrical specimen and, in the low-carbon welds, to permit the maximum "picking up" of alloying elements from the base metal. Table III gives the average thickness of reinforcement (for both sides) of the butt joints in percentage of the base metal thickness.

TABLE III.—AVERAGE TOTAL THICKNESS OF REINFORCEMENT OF BUTT JOINTS IN PERCENTAGE OF BASE METAL THICKNESS

| Type of weld | Sheet thickness, inch | | | | Tube size $1\frac{1}{4}$ by 0.053 inch |
|-----------------------------------|-----------------------|-------|-------|-------|--|
| | 0.031 | 0.063 | 0.125 | 0.188 | |
| Low-carbon, percent..... | 143 | 126 | 122 | 83 | 113 |
| Carburizing flux, percent..... | 189 | 121 | 89 | 85 | 124 |
| Chromium-molybdenum, percent..... | 235 | 100 | 111 | 92 | --- |

HEAT TREATMENT

All heat treatment was done by the Division of Metallurgy, National Bureau of Standards. For the normalizing and hardening operations the temperatures given in the chart "Heat treatment and inspection test of aircraft metals—Naval Aircraft Factory", serial no. ML-79L, September 15, 1932, were used.

The lattice and T joints were hardened by heating at 1,600° F. in a gas furnace for 1 hour and quenching in oil. They were tempered at 900° F. for 1 hour and cooled in air. Tensile and compressive specimens of the tubing from which the joints were made were given the same heat treatment.

The butt and cross joints that were heat-treated were hardened by heating at 1,600° F. for 45 minutes and quenching in oil. They were then tempered at 500°, 700°, 900°, and 1,100° F., respectively, for 45 minutes and cooled in air. Specimens that were normalized

IDENTIFICATION OF T AND LATTICE JOINTS

As in the previous investigation, three specimens were made of each joint. When reference is made to a group of triplicate specimens of the same design a specimen

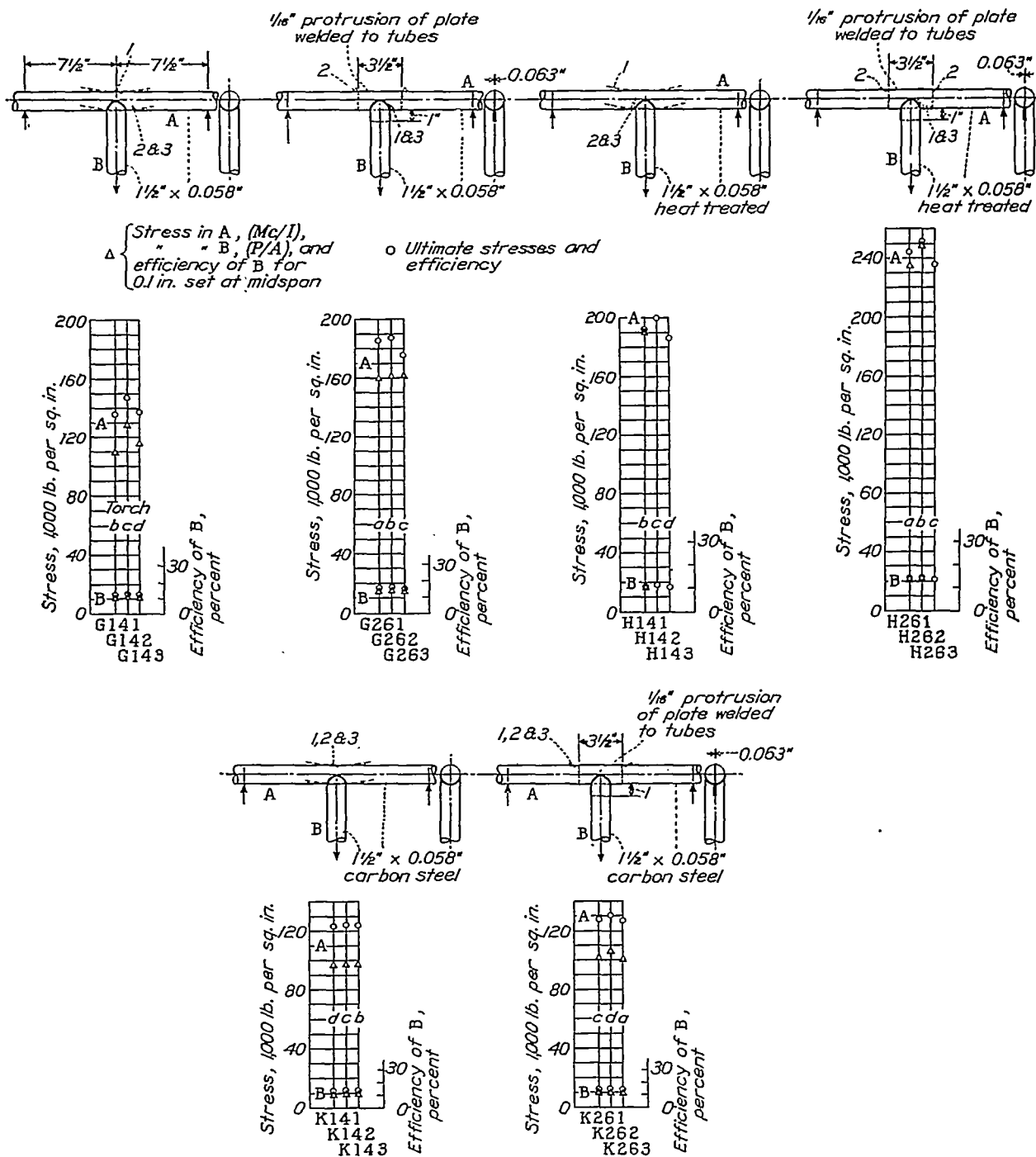


FIGURE 10.—Results of the transverse test of T joints made with chromium-molybdenum steel (upper) and carbon steel (lower) and low-carbon welds. Tube B was loaded in tension with tube A supported at a span of 15 inches. The load producing a permanent set of 0.1 inch at midspan was determined, also the maximum load. The stress M_c/I for tube A was computed for both loads, also the tensile stress and efficiency for tube B.

were held at 1,600° F. for 1 hour and cooled in air. To prevent oxidation a reducing atmosphere was maintained in the furnace for all heating operations above 500° F.

number terminating in a cipher is used, thus, 260; specimens numbered 261, 262, and 263 are the triplicate specimens comprising joints 260. Letters prefixed to the specimen numbers have the following meaning:

*Meaning**Letter*

- G Joint made with $1\frac{1}{2}$ by 0.058-inch chromium-molybdenum tubing and low-carbon weld
- H Joint made with $1\frac{1}{2}$ by 0.058-inch chromium-molybdenum tubing and low-carbon weld, heat-treated after welding
- J Joint made with $1\frac{1}{2}$ by 0.020-inch chromium-molybdenum tubing and low-carbon weld
- K Joint made with $1\frac{1}{2}$ by 0.058-inch carbon-steel tubing and low-carbon weld
- L Joint made with $1\frac{1}{2}$ by 0.020-inch chromium-molybdenum tubing and carburizing flux weld
- M Cantilever loading of T-joint

increasing loads, the load producing a permanent set of 0.1 inch at midspan was determined (loading I). As it was believed that a determination of the bending strength of tube A would be more valuable than the results of loading II (see p. 25 and fig. 7, N. A. C. A. Technical Report No. 348), in which tube A was supported at the joint and tube B loaded until failure occurred, loading I was continued to failure.

Unreinforced T joints, 140, were tested in the heat-treated condition, H140, figure 10.

In an attempt to improve the design of the T joints in the previous investigation, joints 260 were made by inserting a T-shaped gusset plate in slots in the tubes, allowing the edge of the plate to protrude slightly, G260, H260, and K260 (fig. 10).

Carbon-steel joints, K140 and K260 (fig. 10) were tested.

Since the transverse strength of tubing increases with a decrease in the ratio of diameter to wall thickness, in order to investigate joints in tubing having a

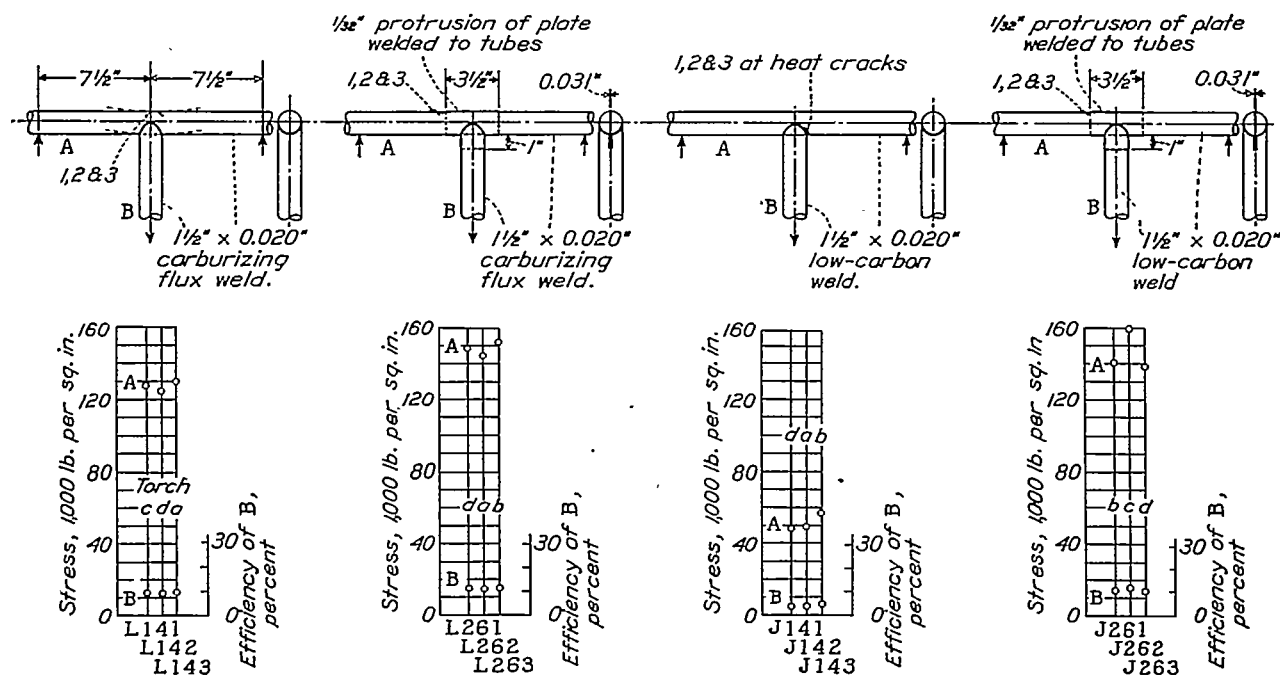


FIGURE 11.—Results of transverse test of T joints made with thin-walled chromium-molybdenum steel tubing.

T JOINTS

TRANSVERSE LOADING

Drawings of the T joints are shown in figures 10 and 11. The method of testing the T joints was changed slightly from the procedure followed in the previous investigation. Tube A was supported on rollers over a span of 10 diameters (15 inches) on the platen of a pendulum hydraulic testing machine (fig. 6, N. A. C. A. Technical Report No. 348). The free end of tube B was gripped in the lower jaws of the machine and load applied. By applying and releasing a succession of

greater ratio of diameter to wall thickness than is ordinarily used in aircraft construction, joints J140, J260, L140, and L260 (fig. 11) were included. Chromium-molybdenum tubing $1\frac{1}{2}$ by 0.020 inch was used.

For comparative purposes two nominal stresses in tube A of the T joints were computed, corresponding to loads in B which produced in A a permanent set of 0.1 inch, and failure, respectively. These stresses were computed like moduli of rupture, by dividing the bending moment at midspan by the section modulus of the original tube (that is, the gusset plates, if any, and tube B were neglected); they are plotted in figures 10 and 11.

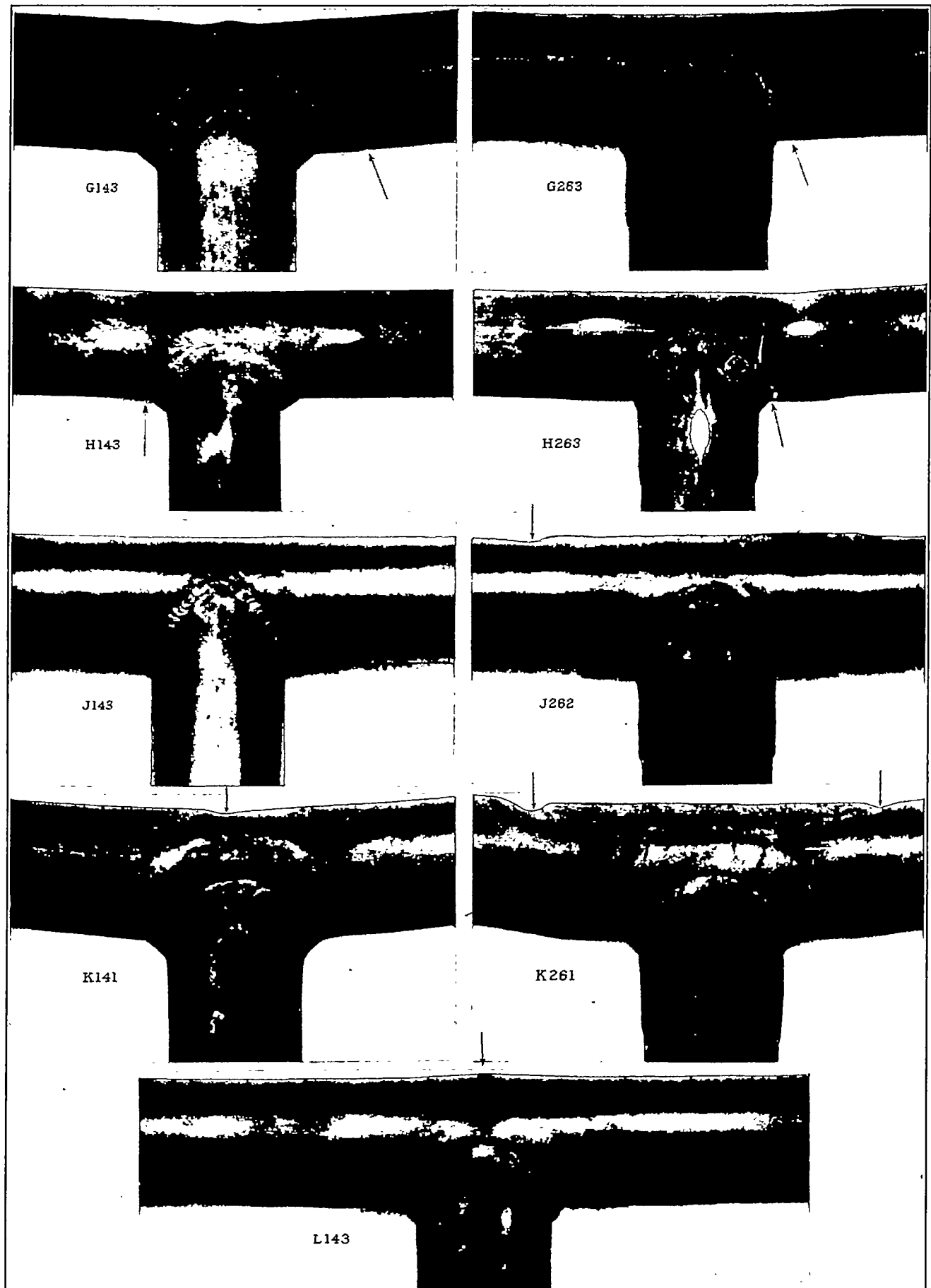


FIGURE 12.—T joints after failure under the transverse loading.

It should be emphasized that while these stresses are a convenient means of comparing the results obtained on different joints of the same size and same size of tubing, the extent to which they could safely be used with other sizes of tubing and different relations of bending moment to shear has not been investigated.

The stresses in tube B at 0.1 inch set and at failure of tube A have been plotted in figures 10 and 11. The ratios of these stresses to the tensile strength of tube B have been denoted the efficiencies of tube B. They indicate the extent to which the strength of the material of tube B has been fully utilized in the joint. The efficiencies are also shown in figures 10 and 11.

Typical failures of T joints under transverse loading are shown in figure 12. The failures are also indicated in figures 10 and 11 by the specimen numbers 1, 2, and 3 at the points of failure. Thus for joints G140, figure 10, the numbers 1, 2, and 3 indicate that specimen G141 failed by buckling and specimens G142 and G143 failed at the bottom of tube A at the locations shown. All the failures at the top of tube A were buckling failures. The failures at other locations were ruptures of either tube A or the weld.

The ratio of the stress for 0.1 inch set to the ultimate stress was much higher for the heat-treated joints than for those which had not been heat-treated. Specimens H142, H143, and H263 failed before the set became 0.1 inch. The strengths of the gusset-reinforced joints G260 under transverse loading were about 31 percent greater than those of the unreinforced joints G140, and the stress which produced a 0.1-inch permanent set in tube A was about 37 percent higher. The heat-treated joints H260 were about 26 percent stronger than the unreinforced heat-treated joints H140.

The carbon-steel joints K140 and K260 had about the same strength. Thus there appears to be little advantage in adding a reinforcing gusset to a carbon-steel T joint.

T joints L140 and L260, figure 11, made with thin-walled tubing by the carburizing flux process, had somewhat lower strengths under transverse loading than joints made from heavier tubing because the thin-walled tubing buckled under lower stresses. There were cracks in joints J140 (see fig. 7), made with low-carbon welds, that greatly lowered the strength of these joints. Cracks were also found in joints J260, made in the same way. The cracks in joints J260 were smaller and did not lie in such a highly stressed portion of the joints as in joints J140. They apparently did not lower the strengths, which were about the same as those of joints L260. All of the joints made with thin-walled tubing failed before developing 0.1-inch set.

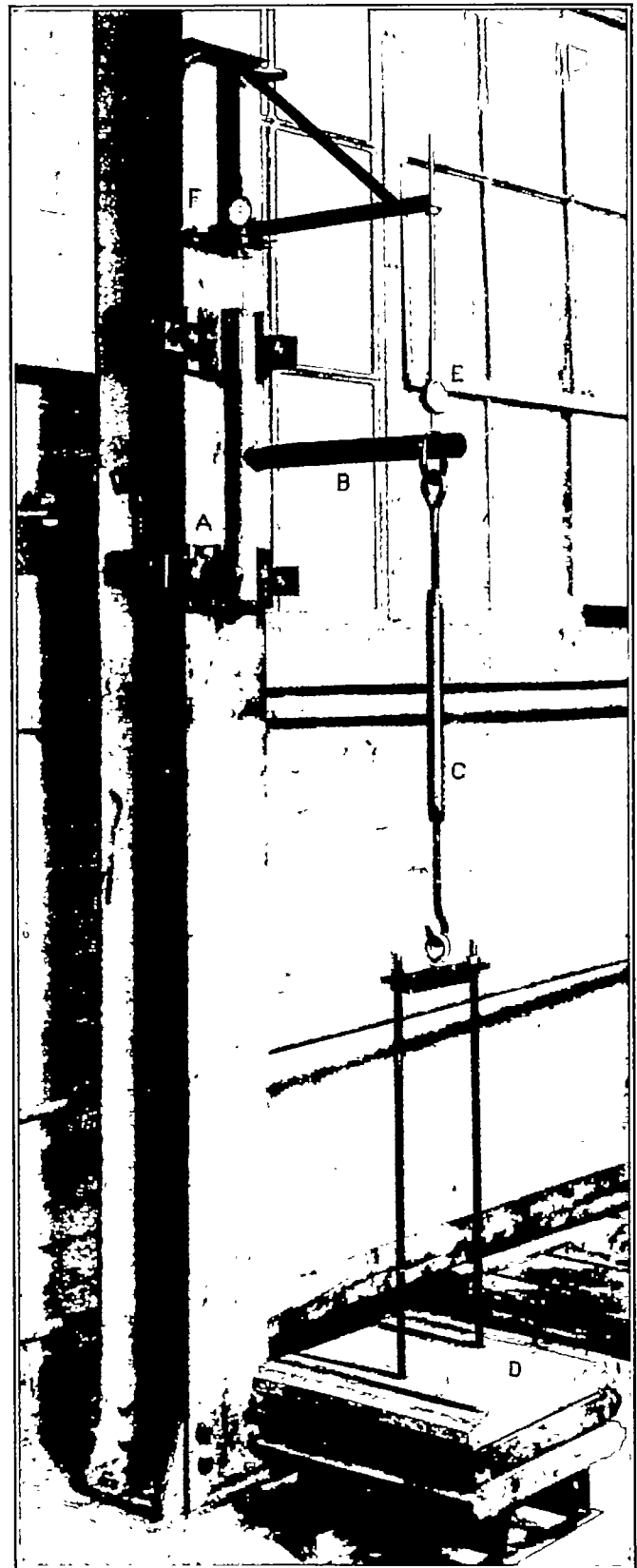


FIGURE 13.—Applying the cantilever leading to a T joint. The weights D were applied by turning the turnbuckle C. The permanent set at E was measured by the dial micrometer.

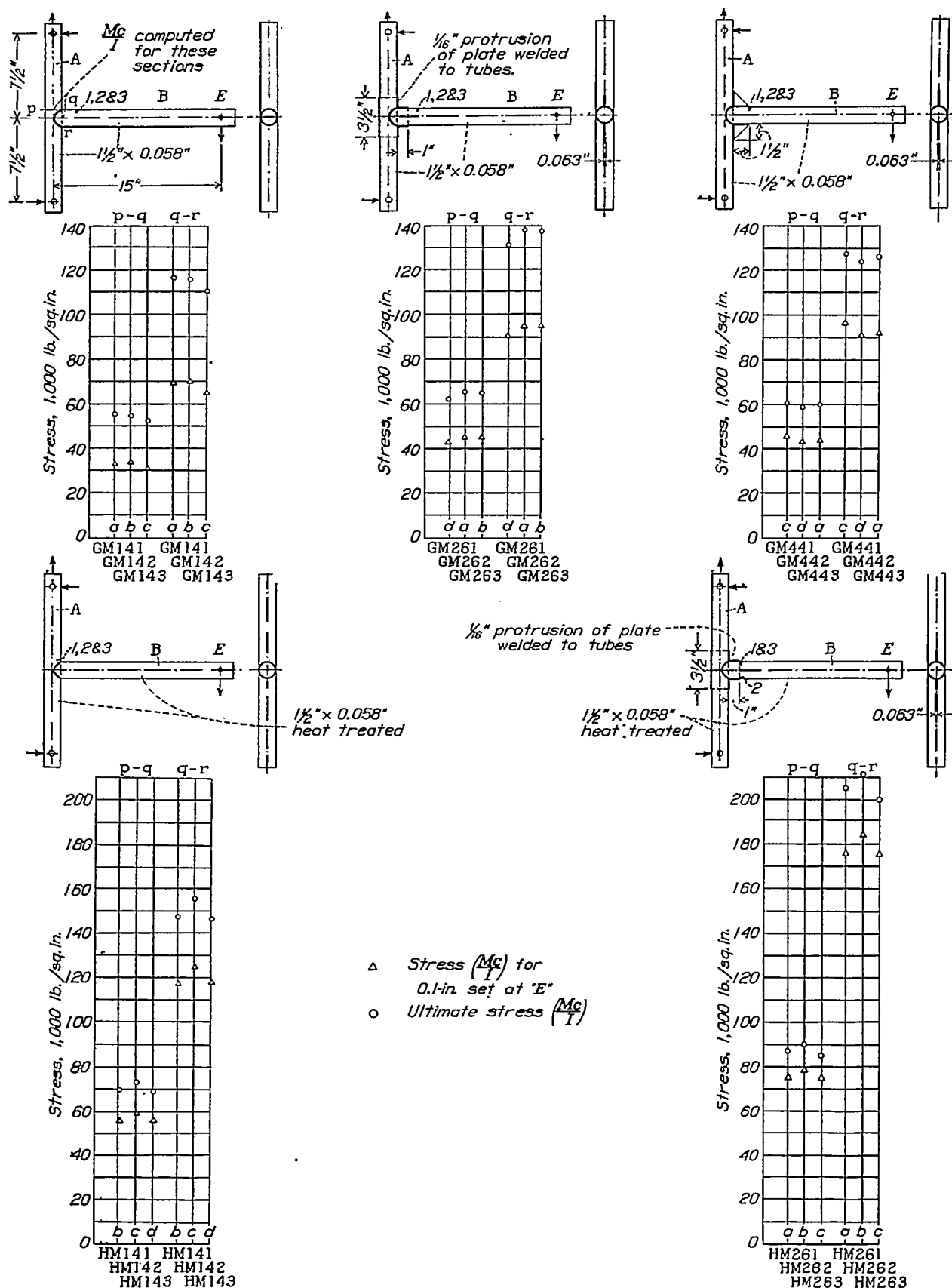


FIGURE 14.—Results of the cantilever test of T joints made with chromium-molybdenum steel and low-carbon welds. The stress $\frac{Mc}{I}$ was computed at section p-q in tube A (see upper left diagram) and at section q-r in tube B for the load producing 0.1 inch permanent set at E and for the maximum load.

CANTILEVER LOADING

It was believed that information regarding the strength of T joints in which the leg of the T was loaded as a cantilever beam would be valuable. Joints were therefore tested as shown in figure 13. Tube A was held in a vertical position between two pins, the upper of which was fixed and the lower was fitted with rollers, allowing movement in a vertical direction. The load was applied by turning the turnbuckle C until the weights D were raised. The dial F measured any movement of the support during loading. No appreciable movement was observed. The pins supporting tube A were spaced 15 inches apart and the length along tube B from the center line of tube A to the

any) were neglected in computing the section modulus. Typical failures are shown in figure 16.

Joints GM260, reinforced by an inserted gusset plate, were about 19 percent stronger than the unreinforced joints GM140. Each failed in tube B where the tube had been annealed during welding.

Joints GM260, reinforced by an inserted gusset plate, were stronger than joints GM440, reinforced by triangular gusset plates.

The unreinforced heat-treated joints HM140 failed by tube B tearing out of the wall of tube A on the upper side. The reinforced heat-treated joints HM260 were about 37 percent stronger than joints HM140 and failed by rupture of tube B at the end of the gusset plate.

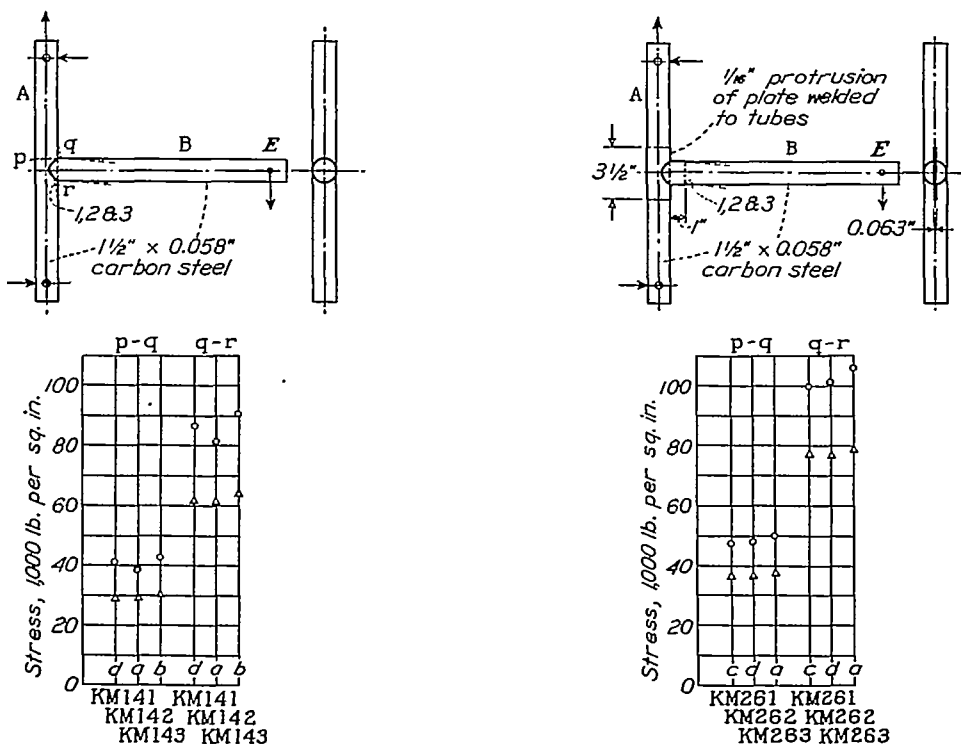


FIGURE 15.—Results of the cantilever test of T joints made with carbon steel and low-carbon welds.

point where the load was applied was 15 inches. The load producing 0.1-inch permanent set at the point of loading E was determined, as well as the maximum load. A dial micrometer was used to measure the permanent set.

Figure 14 shows the test results for "cantilever-loaded" T joints made with chromium-molybdenum steel in both "as welded" and heat-treated conditions. Figure 15 shows test results for similar joints made with carbon steel "as welded."

In figures 14 and 15 the stress at section p-q in tube A and at section q-r in tube B has been plotted for the load which produced a permanent set of 0.1 inch at point E. The stress at failure has been plotted also. The stresses were obtained by dividing the bending moment by the section modulus. The gusset plates (if

The carbon-steel joints KM140, figure 15, failed by bending of tube B without rupturing or buckling. In joints KM260 tube B buckled on the compression side at the end of the gusset plate.

LATTICE JOINTS

The form of specimen and method of testing used for lattice joints was the same as in the previous investigation. The angle between tubes A and B and between B and C (figs. 17 and 18) was 60°. The ends of tubes A and C were supported on pin bearings in the testing machine as shown in figure 8, N. A. C. A. Technical Report No. 348, and tube B was loaded in tension until the joint failed.

The new type of inserted gusset reinforcement was also used for the lattice joints. Figure 17 shows joints

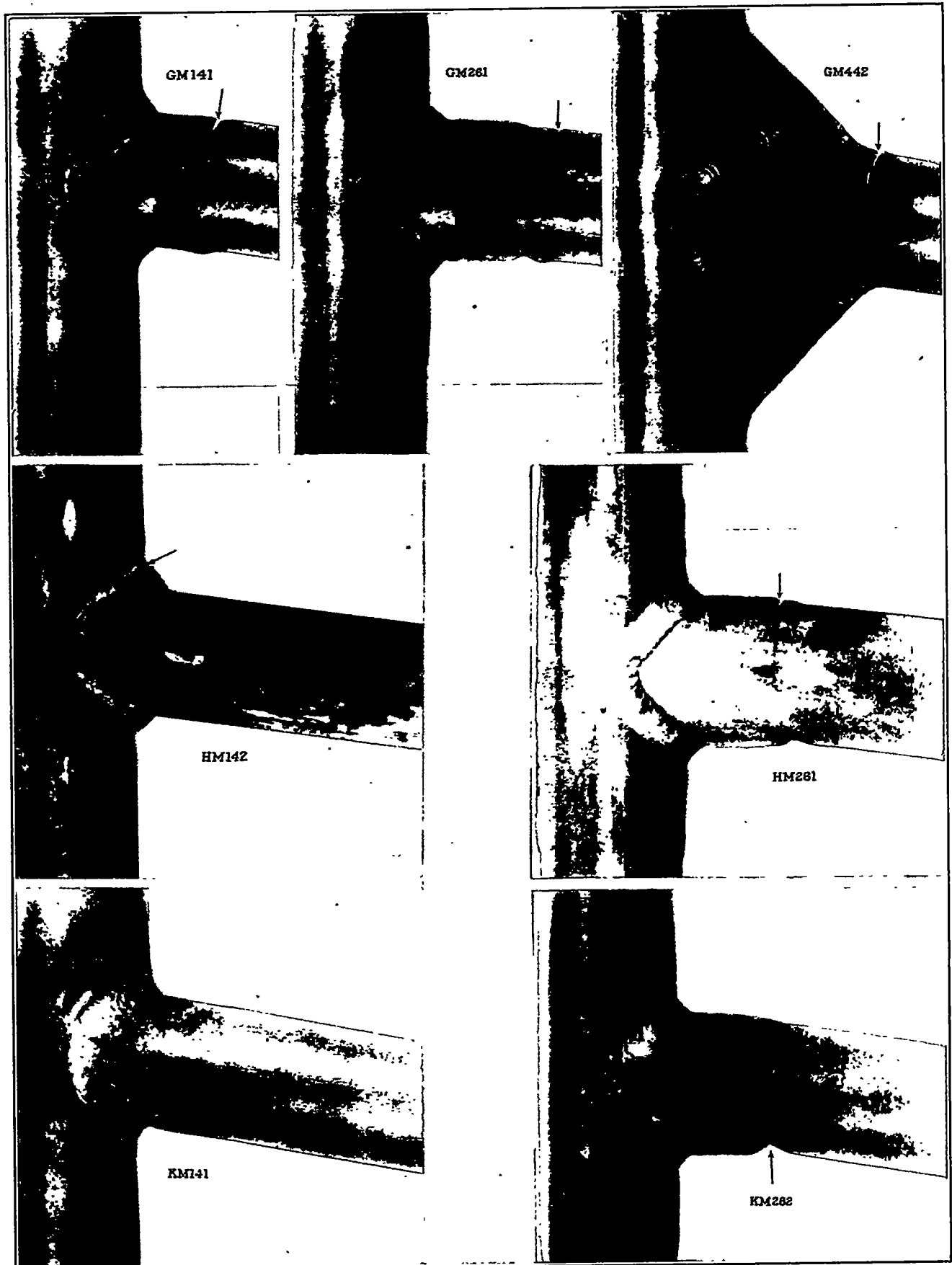
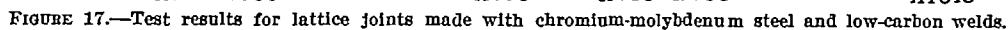


FIGURE 16.—Cantilever-loaded joints after failure.

joints, L630 and K630, figure 18, were made without reinforcement with thin-walled chromium-molybdenum and carbon-steel tubing, respectively.



The unreinforced lattice joints H630, shown in figure 17, were tested in the heat-treated condition. Other

To determine the effect upon the strength of the joint of tubes lying in a plane at right angles to the plane of the tubes to which the loads are applied, lattice joints G1020 were made (fig. 17).

The strap-reinforced joints G1010 tested "as welded" in the previous investigation were found to have a high strength. To determine the strength of this type of joint in the heat-treated condition, joints H1010 shown in figure 17, were made.

plotted on the right side. E_t is the percentage of the tensile strength of tube B developed by the joint and E_c is the percentage of the compressive strength of tubes A and C (both cut from the same length of tubing) developed by the joint. The location of the

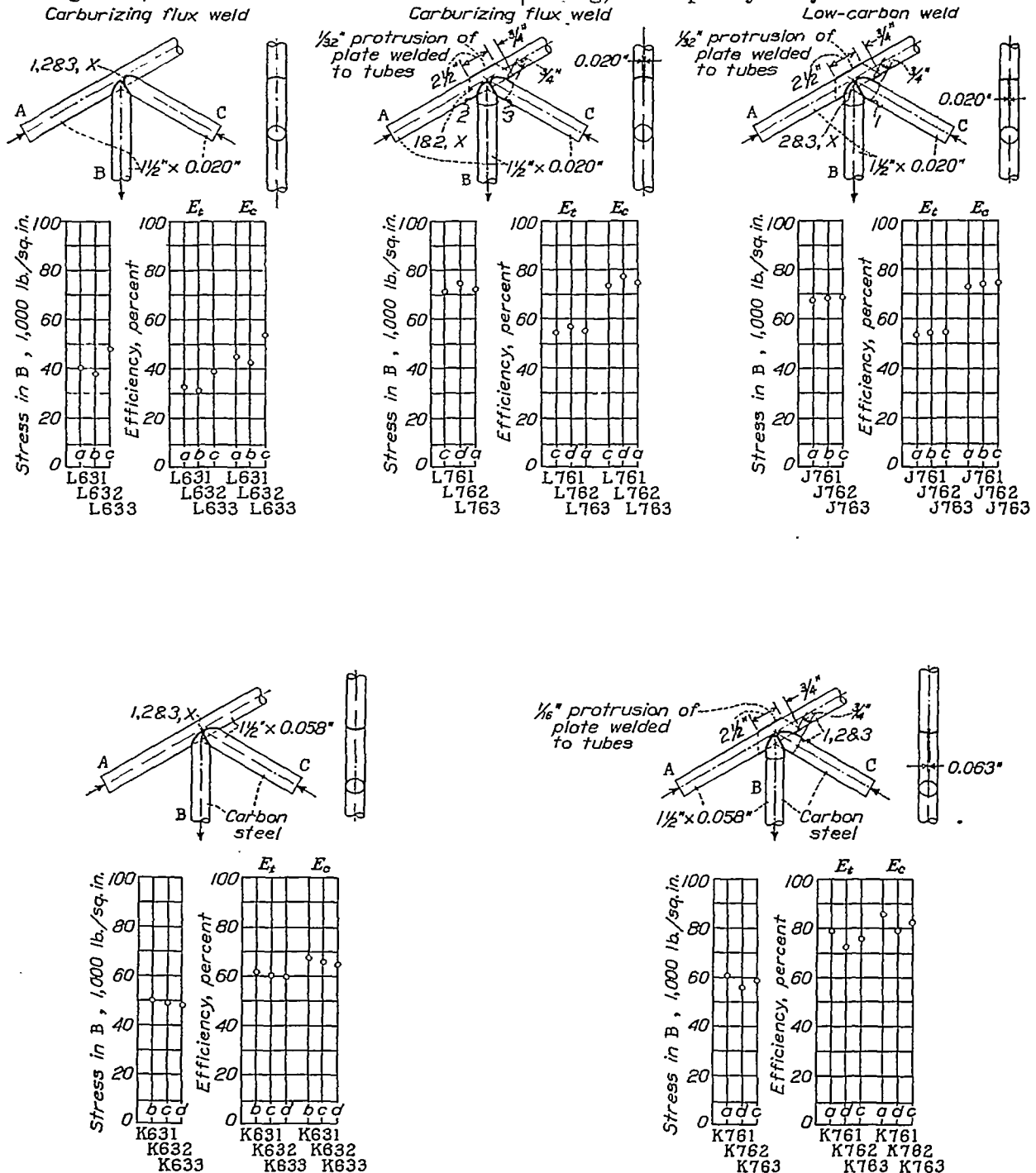


FIGURE 18.—Test results for lattice joints made with carbon-steel tubing and low-carbon welds (lower) and with thin-walled chromium-molybdenum steel tubing (upper).

The results for the lattice joints are plotted in the same manner as in the previous investigation. In figures 17 and 18 the maximum tensile stress in tube B is plotted on the left side of the graphs. The tensile efficiency E_t and the compressive efficiency E_c are

failure is shown on the drawings. Failure by crushing of the tubes at the joint is indicated by X. Typical failures are shown in figure 19.

Joints G760, figure 17, had about the same strength as joints 750 and 1010 (N. A. C. A. Technical Report

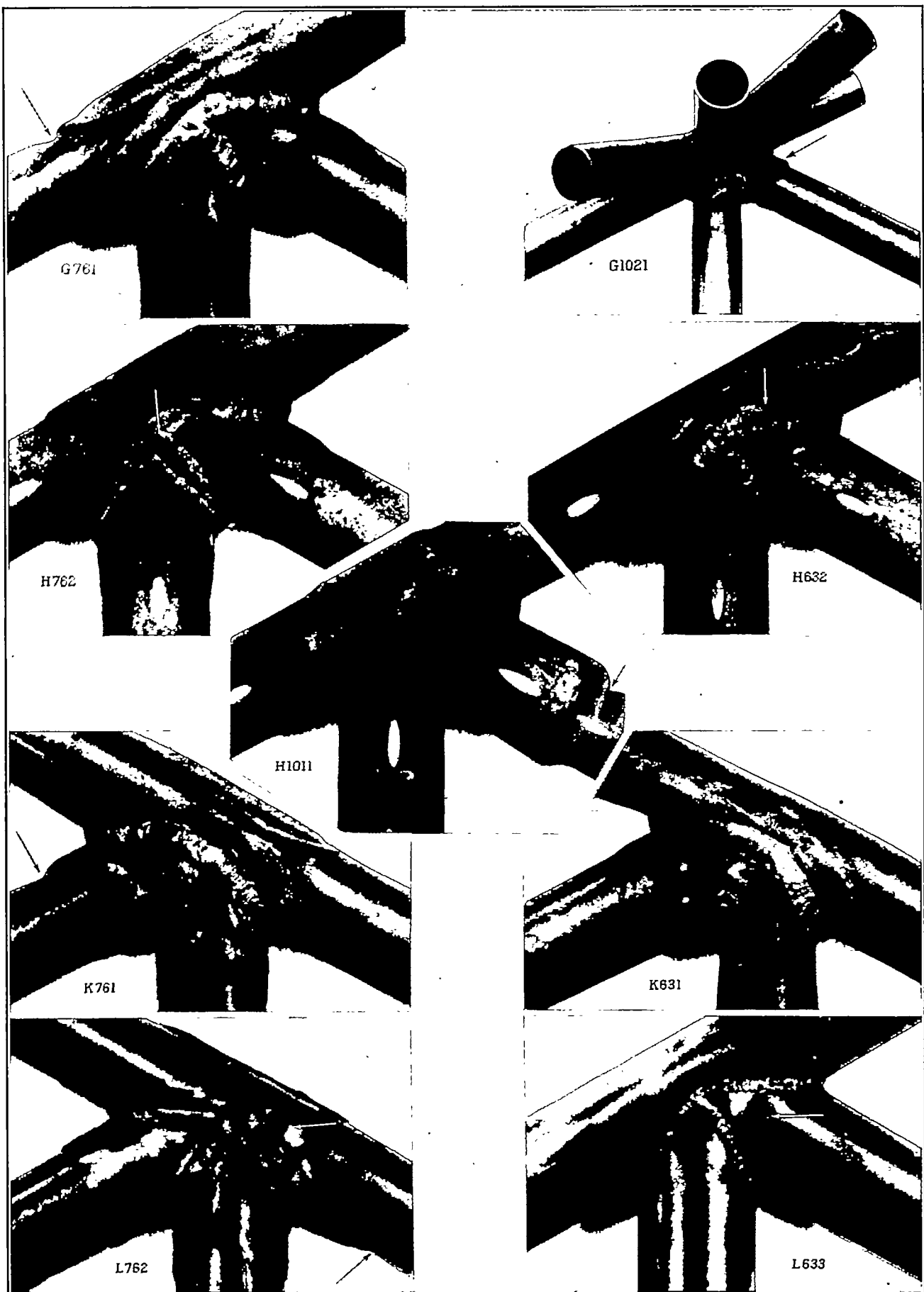


FIGURE 19.—Lattice joints after failure.

No. 348, fig. 27), which were the strongest lattice joints tested in the previous investigation.

The three additional tubes in joints G1020 had a reinforcing effect, as these joints were stronger than joints 630 of the previous investigation.

The strengths of joints 630 were increased by heat treatment, although the tensile and compressive efficiencies were somewhat lowered. Marked increases in the strengths and slight increases in the tensile efficiencies of joints 760 and 1010 were produced by heat treatment. The compressive efficiencies were slightly lowered.

The efficiencies of the joints made from thin-walled tubing, shown in figure 18, were low, especially those of the unreinforced joints L630. Joints J760, for which low-carbon welds were used, have cracks which apparently did not appreciably lower their strengths as their efficiencies were about the same as those of joints L760. The gussets were more effective than in joints made with thicker-walled tubing. The tubes failed by crushing at the joints. The lower strengths of these joints are due to low resistance to lateral crushing or flattening of the thin-walled tubing.

Tensile tests were made of the welded-sheet specimens using either a fluid-support, Bourdon-tube hydraulic machine having dials of 0 to 10,000 pounds, 0 to 50,000 pounds, and 0 to 100,000 pounds capacity or a pendulum hydraulic machine having dials of 0 to 10,000 pounds, 0 to 25,000 pounds, 0 to 50,000 pounds, and 0 to 100,000 pounds capacity.

Templin grips were used for all sheet specimens of which the load did not exceed 10,000 pounds. Specimens having higher strengths were tested in the wedge grips provided with the machine.

Figure 21 shows the four types of fractures of the butt joints for both sheet and tubing. The type of fracture is shown at the top of the diagram in which the test results are plotted. Fractures of type 1 were remote from the weld; type 2 (which occurred for tubular specimens only) in the area where the welding heat had caused a localized annealing effect as shown in figure 17, N. A. C. A. Technical Report No. 348; type 3 at the edge of the weld; and type 4 in the weld. The results for the butt joints in steel sheet are plotted in figures 22 and 23. The strengths of all welds were increased materially by heat treatment, particularly

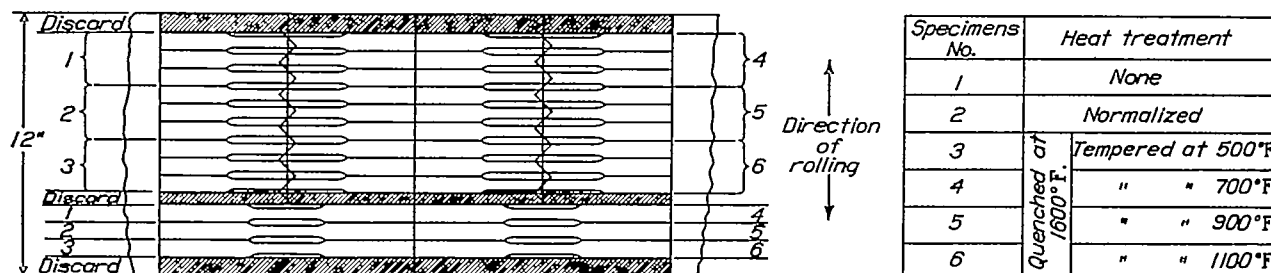


FIGURE 20.—Layout of butt joints and tensile specimens of the base metal in the steel sheets.

The carbon-steel lattice joints, shown in figure 18, had somewhat lower efficiencies than joints made with chromium-molybdenum steel.

BUTT JOINTS

SHEET SPECIMENS

Butt joints were made in chromium-molybdenum sheet and tubing to determine the tensile strengths of heat-treated welds.

Four thicknesses of sheet, 0.031, 0.063, 0.125, and 0.188 inch were used. Open square butt joints were made with the 0.031-inch and 0.063-inch sheets and open 90° single V butt joints with the 0.125-inch and 0.188-inch sheets. All specimens were reinforced on both sides. After welding, tensile specimens were machined from the joints as shown in figure 20. The reduced section was $\frac{1}{2}$ inch wide and $4\frac{1}{2}$ inches long. The weld was at the middle. One series of specimens was made, as shown in figure 20, in each sheet thickness with each of three kinds of welds.

those of the carburizing flux and the chromium-molybdenum welds. There was considerably more scatter in the results of the heat-treated low-carbon welds than in the other types.

In general the full strength of the base metal was realized in the "as welded" and normalized joints in all four sheet thicknesses. Of the joints which were quenched and tempered the carburizing flux welds developed the highest strengths for all tempers in the 0.031-inch sheet thickness. In the other thicknesses the strength of the carburizing flux welds was slightly greater and somewhat more uniform than that of the chromium-molybdenum welds except at the 500° F. temper.

There was some variation in the bead reinforcement (see table III) between specimens of different sheet thicknesses and types of weld. However, none of the chromium-molybdenum welds and only three of the carburizing flux welds (one in the 0.063-inch and two in the 0.188-inch sheet, all quenched and tempered at 500° F.) fractured in the welds, indicating that the



FIGURE 21.—Butt joints in chromium-molybdenum sheet and tubing after failure, illustrating the four types of failure designated in figures 22, 23, 28, 29, and 30.

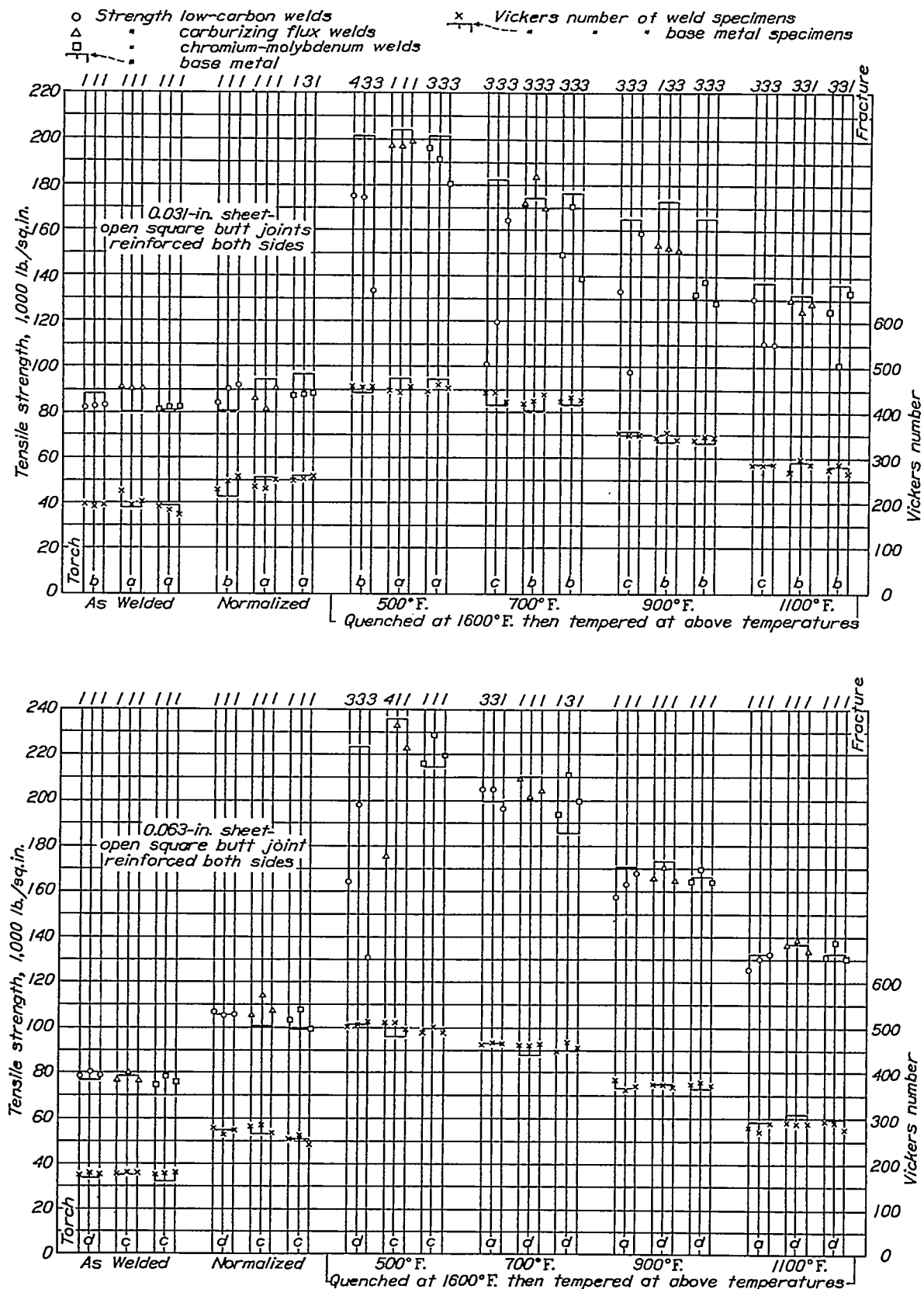


FIGURE 22.—Test results for open square butt joints in 0.031-inch chromium-molybdenum sheet (upper) and in 0.063-inch sheet (lower). Three groups of specimens corresponding to three types of welds were used for each heat treatment. An additional specimen of base metal representing each group of triplicate specimens was heat-treated and tested. The points shown on the graph are the tensile strengths and Vickers numbers of the joints. The corresponding values for the base metal specimens are shown by horizontal lines. The type of fracture of the joints is indicated at the top of the graph; the torch used, at the bottom.

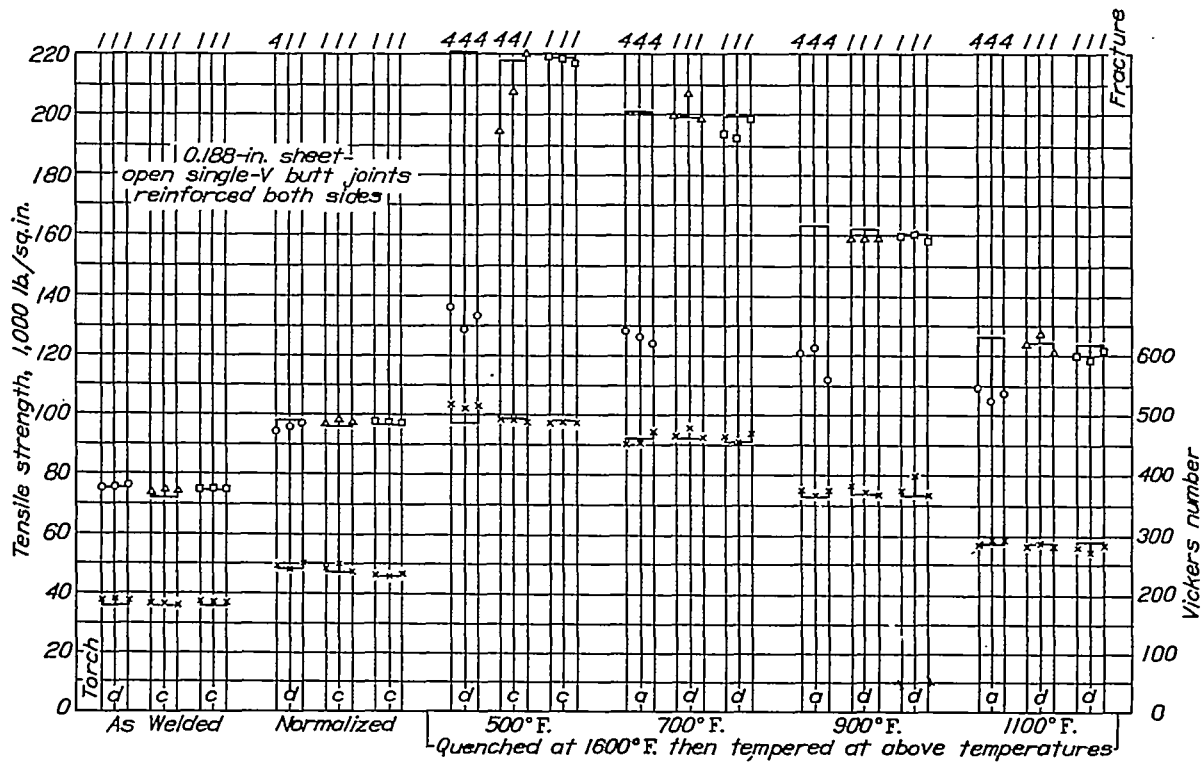
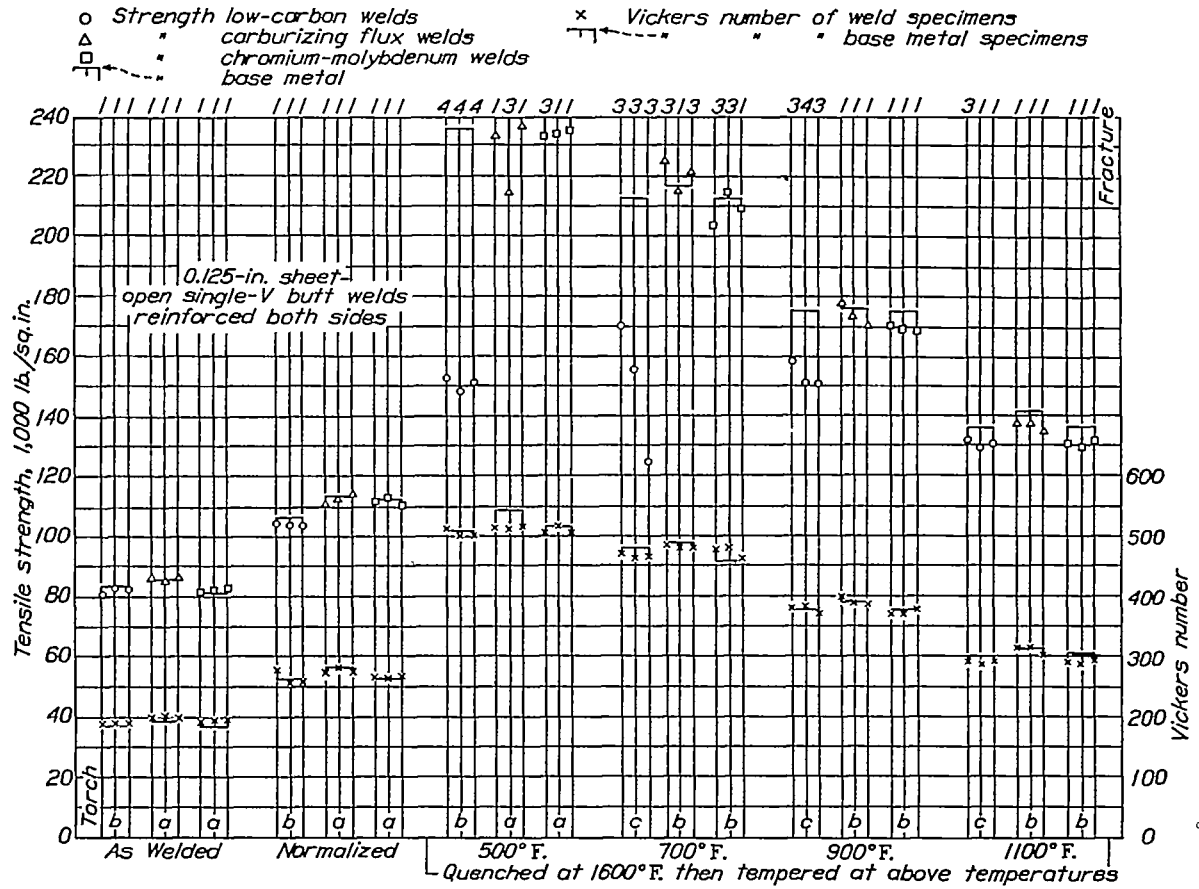


FIGURE 23.—Test results for open single-V butt joints in 0.125-inch chromium-molybdenum sheet (upper) and 0.188-inch sheet (lower).

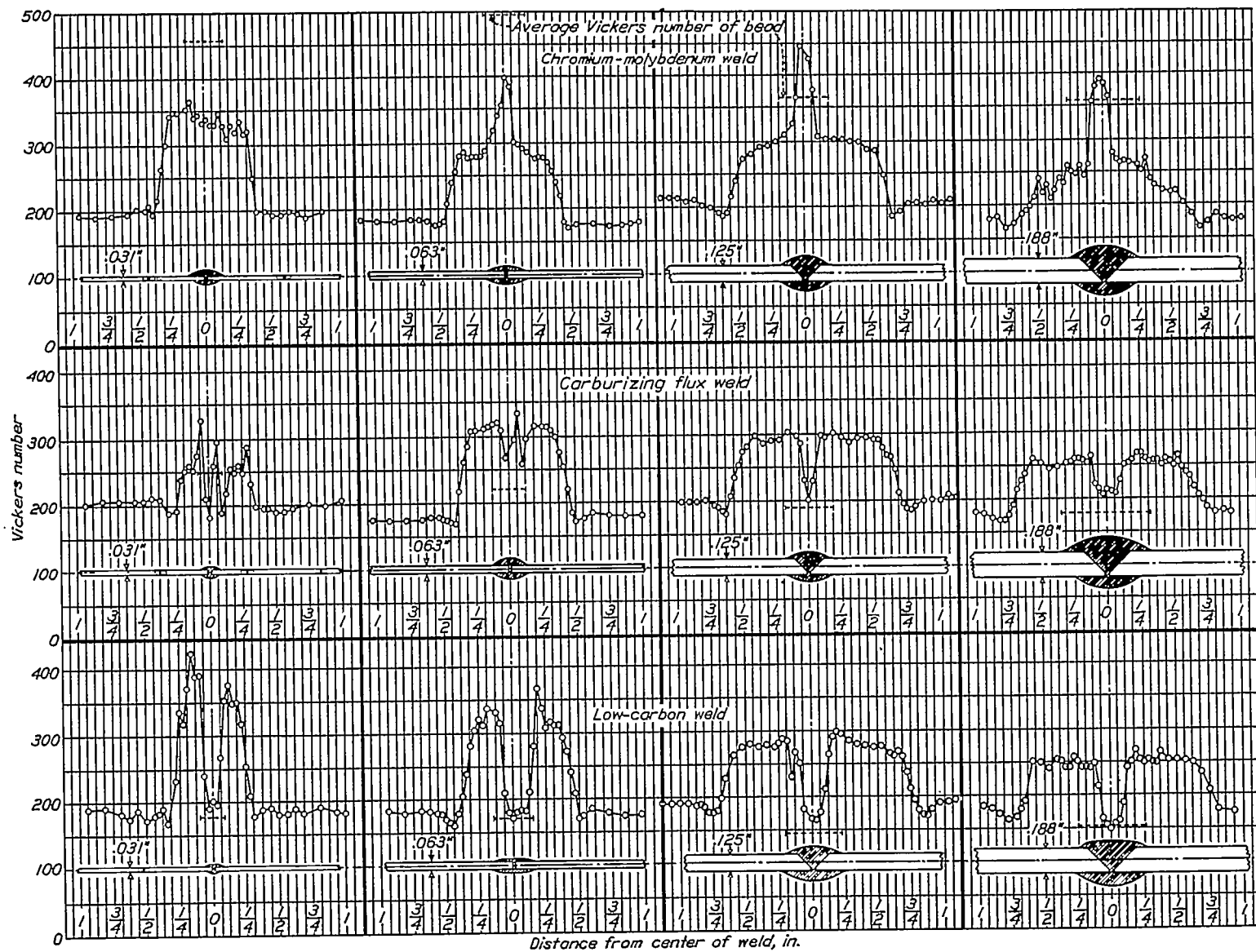


FIGURE 24.—Vickers number of open butt joints in chromium-molybdenum sheet "as welded." The impressions were made on the edge of the specimens.

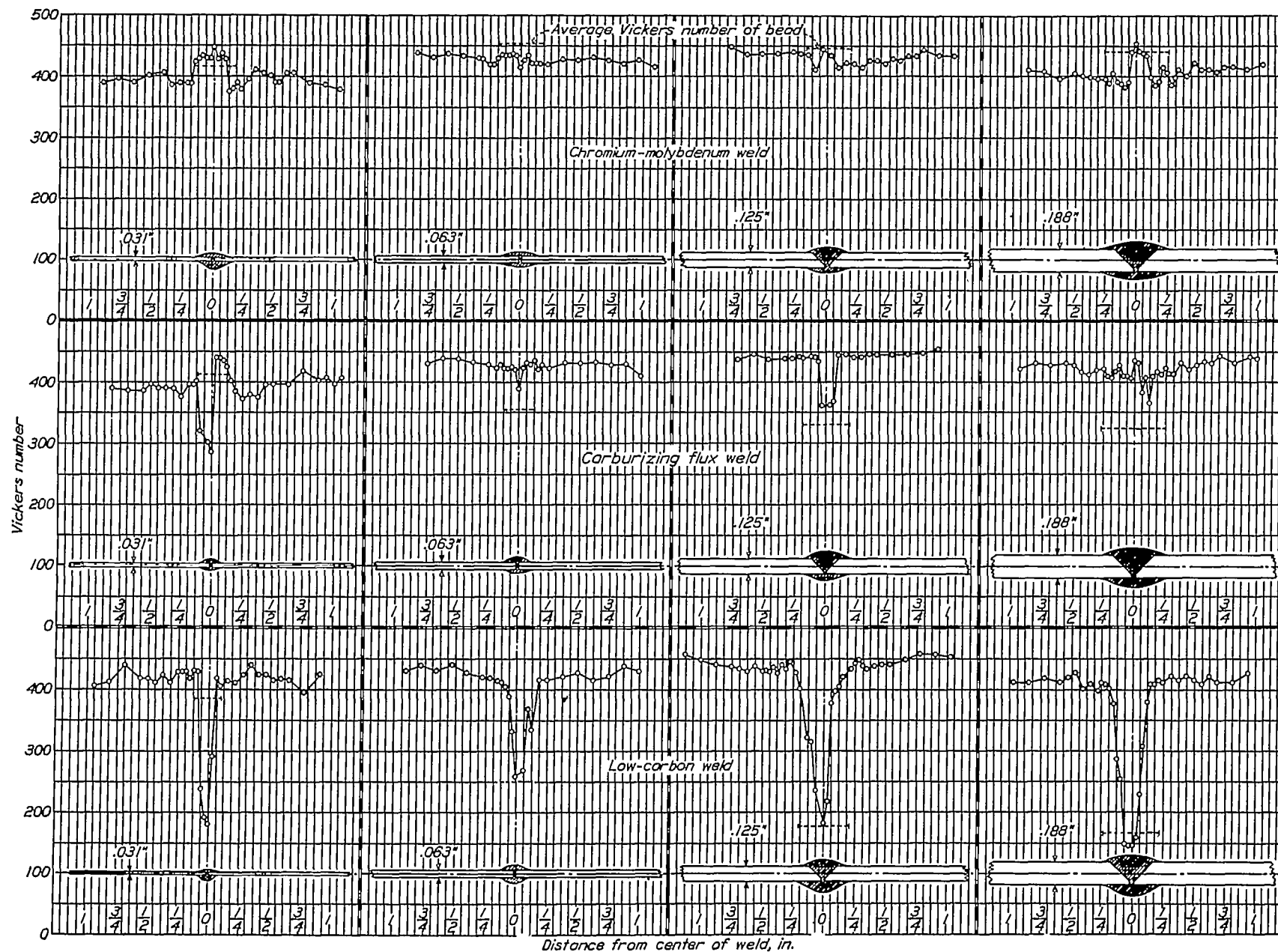


FIGURE 25.—Vickers number of open butt joints in chromium-molybdenum sheet heat-treated after welding by quenching from 1000° F., then tempered at 700° F.

reinforcement was adequate for these welds. Fractures in the weld, type 4, showed a marked reduction in area.

The Vickers explorations shown in figures 24, 25, and 26 were made to study the effect of the heating of the base metal during welding, and the effect of heat treatment after welding. Vickers' impressions were made on the edge of the specimens. The load was varied according to the resistance to indentation and the thickness of the specimen. A 10-kilogram load was gener-

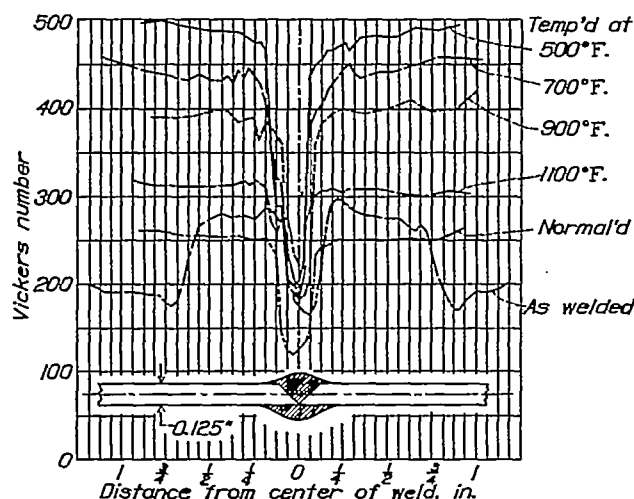


FIGURE 26.—Vickers number of open single-V butt joints in chromium-molybdenum sheet "as welded", normalized and quenched and tempered at several temperatures.

ally used for the 0.031-inch specimens. For the thicker specimens the load was 30 kilograms when the Vickers number did not exceed about 250, and 50 kilograms for higher Vickers numbers. One series of impressions was taken along the center line of the edge by advancing the specimens longitudinally by means of a lead screw. These impressions were spaced from one thirty-second to one-fourth inch apart. In addition, impressions were made on the bead at from two to six points (depending on its size) located as close as pos-

The Vickers number of specimens that had been quenched and tempered at 700° F. are shown in figure 25. The Vickers number of the bead was greatest in the chromium-molybdenum welds and lowest in the low-carbon welds. The thinner sheets in the low-carbon and carburizing flux welds had higher numbers. The Vickers number of the base metal was uniform outside the weld.

Vickers numbers for heat-treated low-carbon welds are shown in figure 26.

TUBULAR SPECIMENS

Four chromium-molybdenum tubes ($1\frac{1}{2}$ by 0.058 inch) were laid out, each as shown in figure 27. Low-carbon welds were made in two of the tubes, carburizing flux welds in the other two.

Butt joints were also made in thin-walled tubing $1\frac{1}{2}$ by 0.020 inch and in carbon-steel tubing $1\frac{1}{2}$ by 0.058 inch. These were left "as welded."

The ends of the tubular butt joints were plugged and the specimens were tested in tension using the same apparatus and methods as used for the sheet specimens.

Tubular butt joints (fig. 28) showed more variation in strength than butt joints in sheet. The carburizing flux welds had the highest strengths of any of the quenched and tempered joints. Failure occurred either in the weld or remote from the weld, seldom at the edge. More of the low-carbon welds failed at the edge than in the weld. Those joints that were quenched and tempered showed little difference in strength regardless of tempering temperature.

Results of tests on the thin-walled tubular butt joints are shown in figure 29. All low-carbon welds had cracks (see fig. 7) and failed at these cracks. No cracks were found in the carburizing flux welds. Two of the latter joints failed in the weld, four in the annealed portion of the tube, and one at the edge of the weld. Those failing in the weld had low strengths.

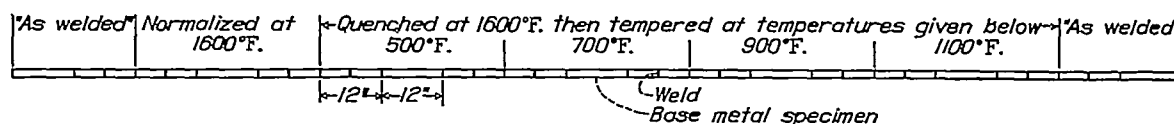


FIGURE 27.—Layout of the tubular butt joints and base metal specimens.

sible to the edge of the cross section. The averages of these are shown in the figures.

Figure 24 shows that the Vickers number of the weld metal in the "as welded" condition varies with the kind of welding rod used. The welding heat caused hardening of the base metal near the weld in a zone varying in width from about $\frac{1}{4}$ to $\frac{3}{4}$ inch on each side of the weld. In this zone the Vickers number was lower in the thicker sheets, probably because of slower cooling of the thicker sheets.

The strengths of the carbon-steel butt joints in $1\frac{1}{2}$ by 0.058-inch tubing are also shown in figure 29.

CROSS JOINTS

Cross joints (shown in fig. 30) were tested to determine the strengths of three types of welds when used to make heat-treated joints in tubes of different thicknesses. These joints consisted of two chromium-molybdenum tubes, 1 by 0.035 inch, lying in the same axis, welded to opposite sides of the wall of a much thicker

tube, $1\frac{1}{2}$ by 0.083 inch. Three types of welds were used: (1) low-carbon welds, (2) carburizing flux welds, and (3) a combination of the first two types

as the unreinforced joints 140 and 630 in the previous investigation. As before, no consistent difference in welding speed could be observed for any one torch.

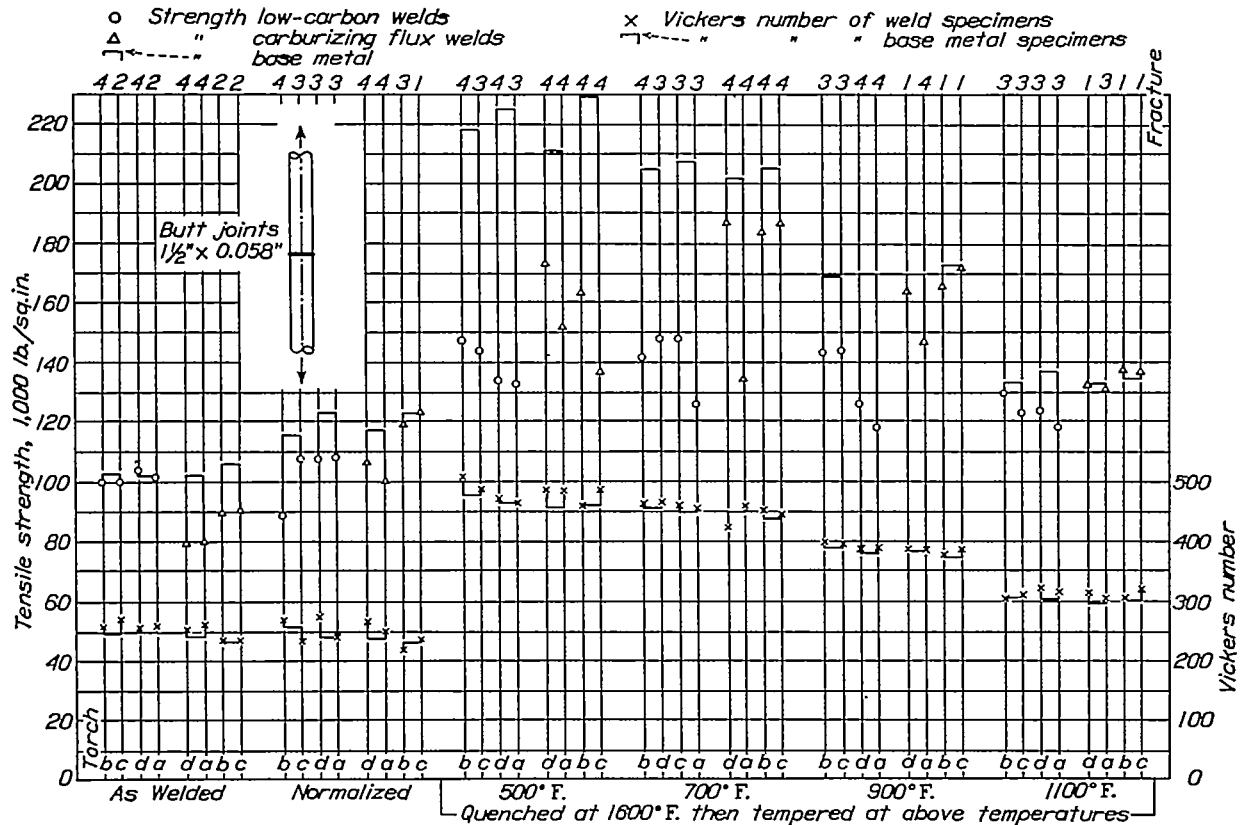


FIGURE 28.—Test results for butt joints in chromium-molybdenum steel tubing $1\frac{1}{2}$ inches O. D. by 0.058-inch wall.

in which the welding rod was the same as used for the carburizing flux welds but in which the base metal was fused, using the neutral flame technique of type (1). The 1 by 0.035 inch tubes were laid out as shown in figure 27.

Tensile tests were made in a 100,000-pound pendulum hydraulic testing machine.

The cross joints had the lowest strengths of any of the heat-treated joints. Practically all joints except those tested "as welded" failed at the edge of the weld. There was no significant difference in strength within the range of tempering temperatures used. The low strengths of these joints were probably due to stress concentrations near the weld caused by the sharp changes in cross section. The joints made by the carburizing flux process were slightly stronger than those made with the same rod, and neutral flame technique. The low-carbon welds had the lowest strengths.

TIME OF WELDING

The time required to machine and weld the joints and the weight of the weld metal and gusset plates are shown in figure 31. The gusset-reinforced joints G260 and G760 required about twice the time to weld

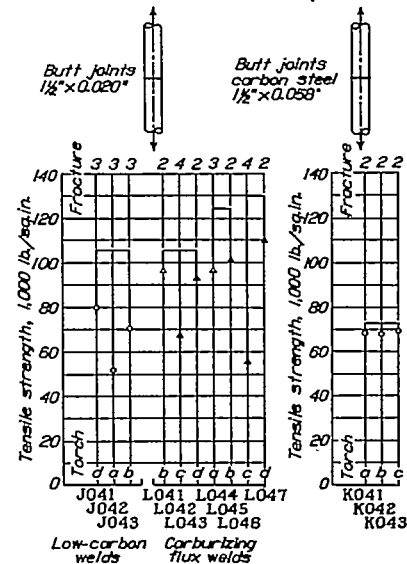


FIGURE 29.—Test results for butt joints in thin-walled chromium-molybdenum steel tubing and in carbon-steel tubing.

MECHANICAL PROPERTIES OF BASE METAL

Tensile tests were made on heat-treated sheet and tubular specimens of the base metal from which the butt and cross joints were made. Stress-strain and

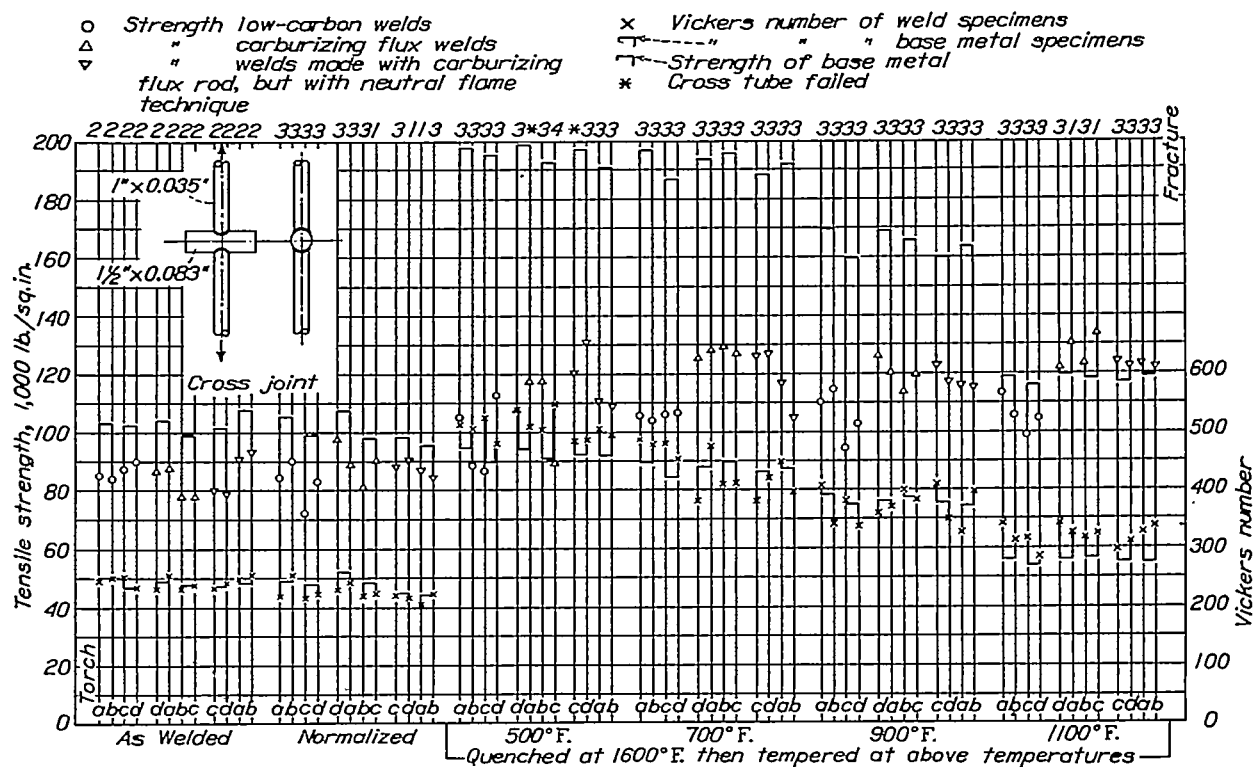


FIGURE 30.—Test results for cross joints in chromium-molybdenum steel tubing.

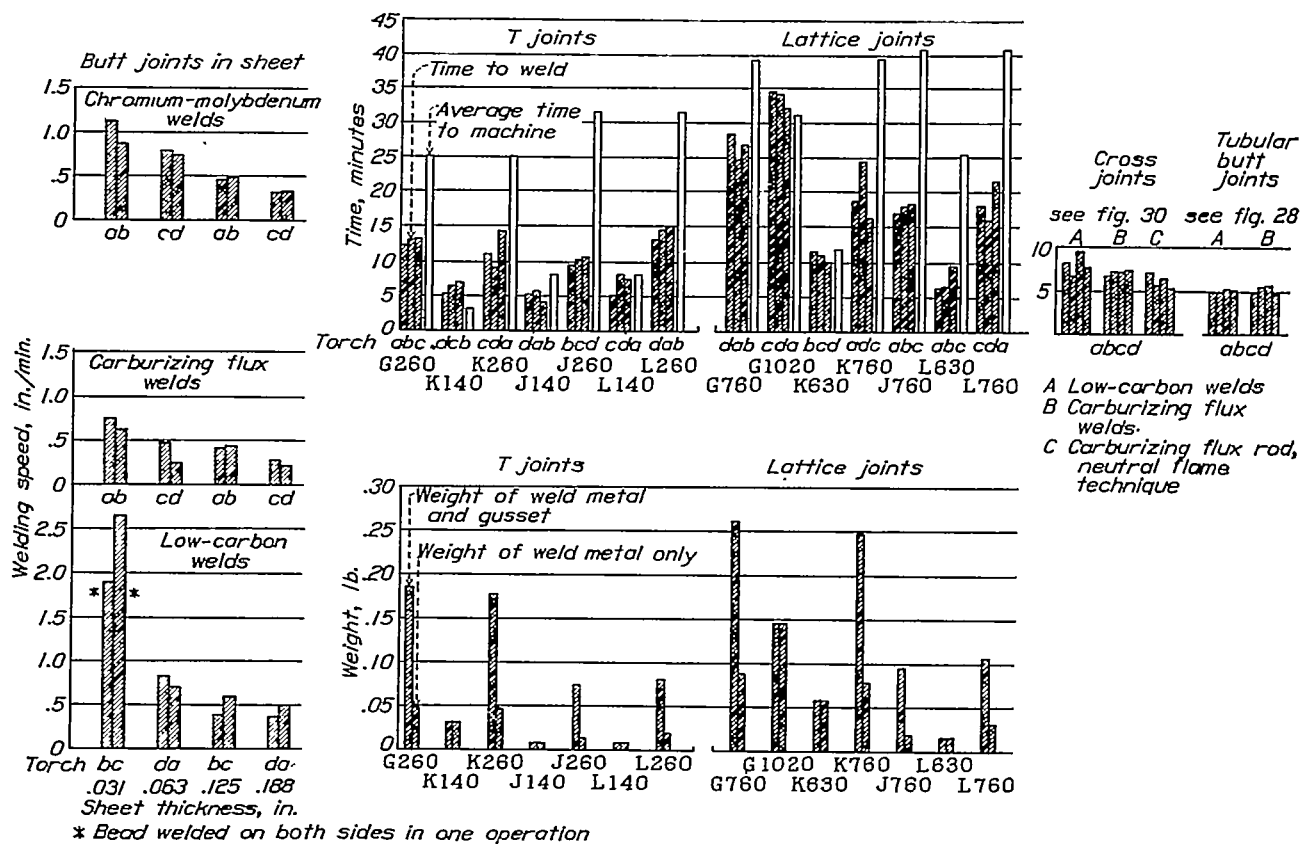


FIGURE 31.—Time required to machine and weld joints; weights of weld metal and reinforcement.

difference curves⁵ (fig. 32) were obtained. The mechanical properties are given in figure 33 for tubular specimens and figure 34 for sheet specimens.

The tubes were tested in full section with steel plugs in the ends. For the sheet the American Society for Testing Materials' standard sheet-metal specimen having a 2-inch-gage length and a width of $\frac{1}{2}$ inch was used.

A Ewing extensometer having a 2-inch-gage length was used to measure the strain.

The yield point was determined as required in Navy Department Specification 44T18a, in which it is de-

tempered at either 700° F. or 900° F. The normalized specimens had comparatively low proportional limits.

Young's modulus increased slightly with the tempering temperature for the sheet specimens and for the 1 by 0.035-inch tubular specimens, but not for the $1\frac{1}{2}$ by 0.058-inch tubular specimens.

The elongation in 2 inches increased with the sheet thickness.

The mechanical properties of the heat-treated chromium-molybdenum sheet are in fair agreement with the properties of similar heat-treated sheet tested by F. T. Sisco and D. M. Warner (reference 5).

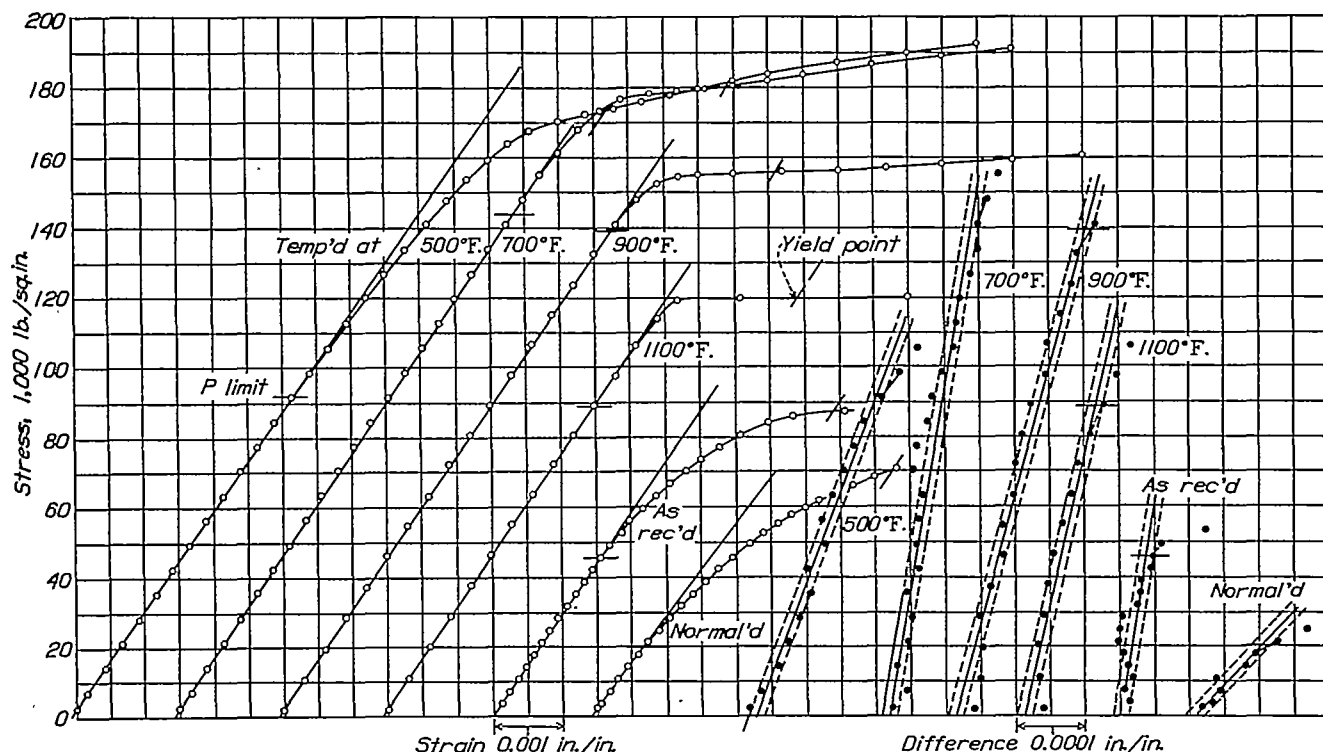


FIGURE 32.—Tensile stress-strain curves for chromium-molybdenum steel tubular specimens $1\frac{1}{2}$ inches O. D. by 0.058-inch wall.

finied as that stress under which the specimen shows a strain 0.002 inch/inch greater than that computed from the formula

$$\text{Strain (in./in.)} = \frac{\text{stress (lb./sq. in.)}}{30000000}$$

The $\frac{1}{8}$ -inch sheet specimens had the highest tensile strengths of all quenched and tempered specimens. When tempered at 500° F. the tensile strength was about 238,000 lb./sq. in.

The yield points of the 1 by 0.035-inch tubular specimens were highest when the specimens were tempered at 700° F.

The proportional limits were the most variable of the mechanical properties. The proportional limits of the tubular specimens were highest when the specimens were

Figure 35 shows the variation of tensile strength with Vickers' number for chromium-molybdenum sheet and tubing.

CONCLUSIONS

1. The magnetic dust-inspection method was quite effective in detecting seams in tubing and cracks in welded joints. This method of inspection could be utilized by manufacturers in the routine examination of steel aircraft materials and welded structures.

2. Based on considerations of strength, weight, welding time, and freedom from cracks, the inserted gusset type of reinforcement used in this investigation for T and lattice joints, is considered to be better than any type tested previously. In increasing the strength of joints this reinforcement was effective for all joints except the carbon-steel T joint under transverse loading.

3. In welding the thin-walled chromium-molybdenum tubing, only the carburizing flux process was

⁵ See N. A. C. A. Technical Report No. 348, p. 6; also discussion by L. B. Tuckerman of the Determination and Significance of the Proportional Limit in the Testing of Metals, by R. L. Templin, presented at the Thirty-second Meeting of the American Society for Testing Materials, June 25, 1929.

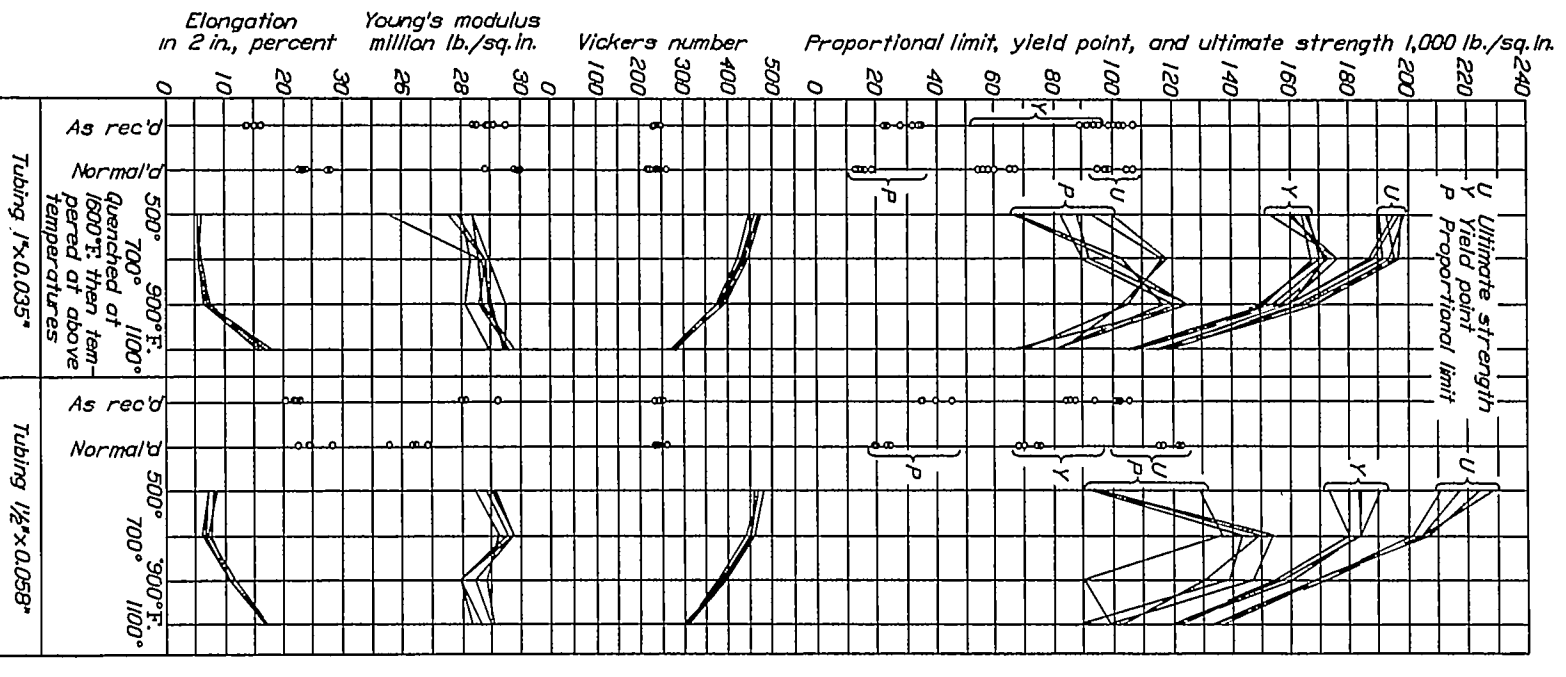


FIGURE 33.—Mechanical properties of two sizes of chromium-molybdenum steel tubing for various heat treatments.

found to produce welds which were free from cracks. T and lattice joints made from this tubing had somewhat lower strengths than joints made from heavier tubing because of failure by local buckling.

4. Normalizing the chromium-molybdenum steel butt joints increased their strengths except in the case of carburizing flux welds in 0.031-inch sheet, which showed a slightly lower strength. Of the sheet specimens heat-treated by hardening and then tempering at various temperatures, the chromium-molybdenum and the carburizing flux welds were approximately equal in strength except in the case of the 0.031-inch sheet which showed a somewhat higher strength for the carburizing flux welds.

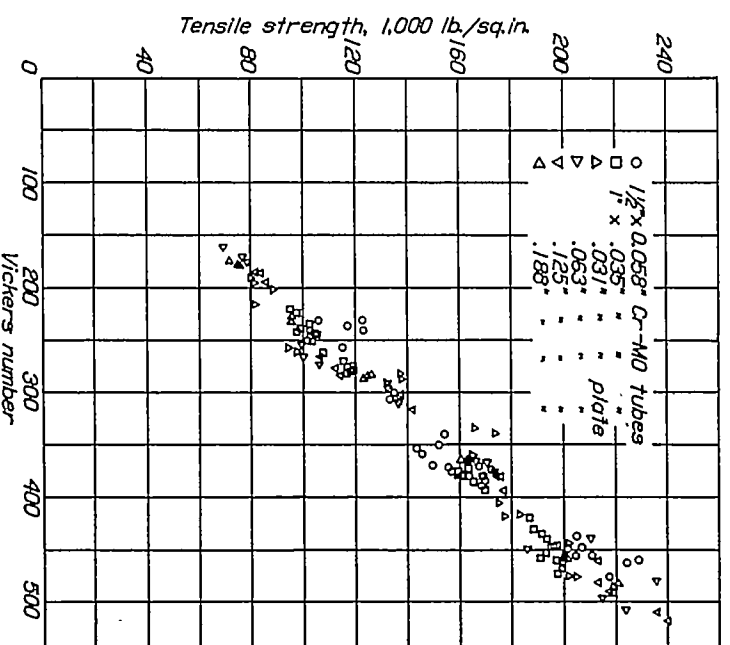


FIGURE 35.—Relation between the Vickers number and the tensile strength for chromium-molybdenum steel sheet and tubing.

5. The strength of the heat-treated butt joints, especially those made with low-carbon welds, was in most cases less uniform than the strength of the base metal. Heat-treated cross joints, in which adjoining tubes had a great difference in diameter and wall thickness, had low strengths compared to the tubular butt joints.

6. As in the first investigation, no consistent difference in strength or speed of welding could be attributed to any one torch.

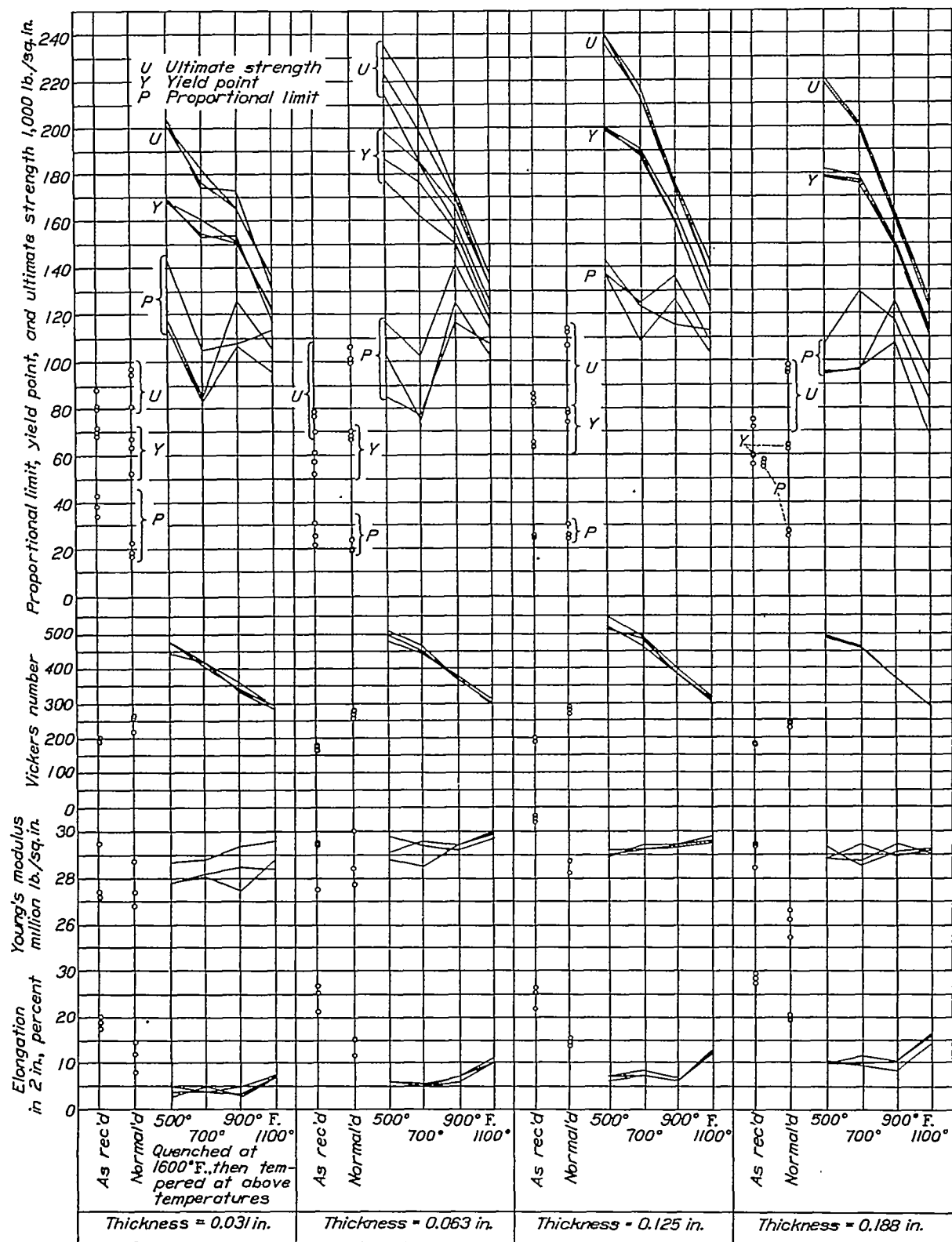


FIGURE 34.—Mechanical properties of four thicknesses of chromium-molybdenum steel sheet for various heat treatments.

ACKNOWLEDGMENTS

Acknowledgment is made to the Air Reduction Sales Co., the Linde Air Products Co., the Torch Weld Equipment Co., and the Bastian-Blessing Co. for lending the torches and equipment; to the Linde Air Products Co. for contributing the services of the welding supervisor, Mr. H. S. George, who rendered invaluable assistance during the welding; to the Keystone Aircraft Co. for assistance in obtaining a welder; to Mr. R. M. Fowler, for making chemical analyses of the material; to Messrs. Louis Jordan and H. E. Francis for heat treating some of the welded joints; and to Mr. R. E. Pollard for making a microscopic examination of seams and cracks.

NATIONAL BUREAU OF STANDARDS,
WASHINGTON, D. C., *August 12, 1936.*

REFERENCES

1. Roux, Albert: Contrôle des Soudures par les Spectres Magnétiques. *Comptes Rendus de L'Académie des Sciences*, vol. 185, October 24, 1927, p. 859.
2. Watts, T. R.: Magnetic Testing of Butt Welds. *Jour. of the American Welding Society*, vol. 9, no. 9, September 1930, p. 49; also Magnetographic Inspection of Welds. *Welding Engineer*, vol. 15, no. 10, October 1930, p. 31.
3. de Forest, A. V.: Non-Destructive Tests by the Magnetic Dust Method. *Iron Age*, vol. 127, no. 20, May 14, 1931, p. 1595.
4. George, H. S.: A New Process for Making Welded Joints. *Jour. of the American Welding Society*, vol. 11, no. 7, July 1932, p. 22.
5. Sisco, F. T., and Warner, D. M.: Effect of Heat Treatment on the Properties of Chrome-Molybdenum Steel Sheet. *Trans. of the American Society for Steel Treating*, vol. 14, August 1923, p. 177.

BIBLIOGRAPHY

In addition to the bibliography given in N. A. C. A. Technical Report No. 348, the following technical papers may be of interest:

1. Whittemore, H. L., Crowe, John J., and Moss, H. H.: Procedure Control in Aircraft Welding. *Proceedings of the American Society for Testing Materials*, vol. 30, Part II, 1930, pp. 140-146.
2. George, H. S.: The Cause and Prevention of Heat Cracks in Aircraft Welding. *Mechanical Engineering*, vol. 53, no. 6, June 1931, pp. 433-439.
3. Beissner, Hans: Einfluss der Gasschmelzschweißung auf die Biegungsschwingungsfestigkeit von Chrom-Molybdän-Stahlrohren. *Z. V. D. I.*, vol. 75, no. 30, July 25, 1931, pp. 954-956.
4. Rechtlich, von Arved: Grundlagen für die konstruktive Anwendung und Ausführung von Stahlrohrschweißungen im Flugzeugbau. *D. V. L. Yearbook*, 1931, pp. 379-438.
5. Jansen, P. N., and Speller, T. H.: An Aircraft Manufacturer's Experience with Welding Quality Control. *Jour. of the American Welding Society*, vol. 12, no. 10, October 1933, pp. 9-13.
6. Müller, J.: Weldability of High-Tensile Steels from Experience in Airplane Construction, with Special Reference to Welding Crack Susceptibility. *T. M. No. 770*, N. A. C. A. 1935.